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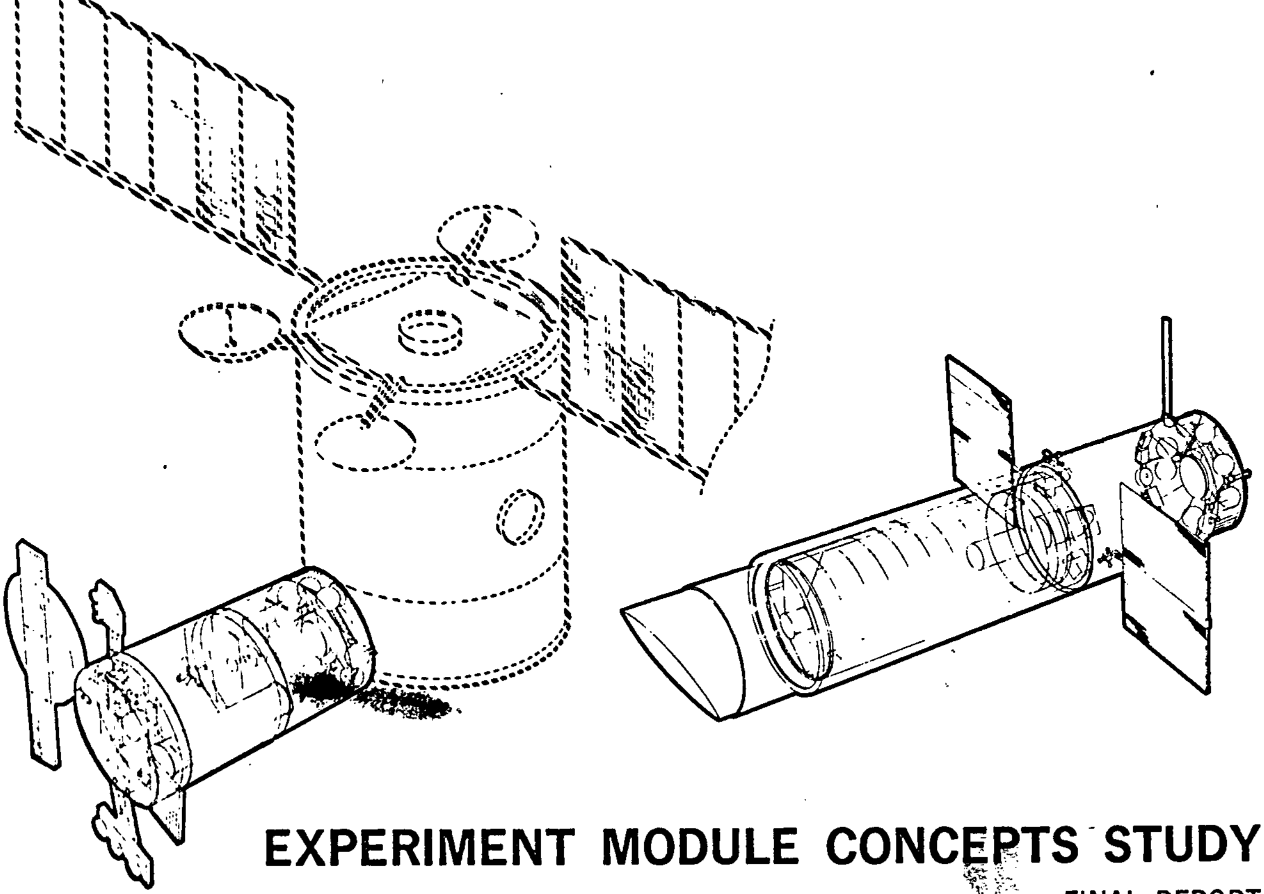
REPORT NO. GDC-DAA70-004 (VOL. I) COPY NO. 001



EXPERIMENT MODULE CONCEPTS STUDY

FINAL REPORT

VOLUME I ✦ MANAGEMENT SUMMARY

October 1970

Prepared for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama
Contract NAS8-25051

Advanced Space Systems, Research and Engineering
CONVAIR AEROSPACE DIVISION OF GENERAL DYNAMICS
San Diego, California

N72-14891 (NASA-CR-103069) EXPERIMENT MODULE CONCEPTS STUDY. VOLUME 1: MANAGEMENT SUMMARY Final Report (General Dynamics/Convair) Oct. 1970 72 p CSCL 22B

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October 1970

Approved by: D. J. Powell

D. J. Powell, Study Manager

W. W. Withee

W. W. Withee, Director
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FOREWORD

This final report is submitted in accordance with the requirements of Appendix 3 — Reports and Visual Aids Requirements, Statement of Work, Experiment Module Concepts Study, Contract NAS8-25051, as amended by Amendment No. 2 dated 9 March 1970.

It comprises the following documents:

Volume I — Management Summary
Volume II — Experiments & Mission Operations
Volume III — Module & Subsystem Design
Volume IV — Resource Requirements
Volume V — Book 1 Appendix A Shuttle-Only Task
Book 2 Appendix B Commonality Analysis, Appendix C Maintenance Analysis

The study was conducted under the program and technical direction of Max E. Nein and Jean R. Olivier, PD-MP-A, of the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. Dr. Rodney W. Johnson, OMSF (Code MF), as study sponsor furnished valuable guidance and assistance.

Other NASA centers and offices made significant contributions of advice, consultation, and documentation to the performance of the tasks whose results are reported here. Personnel from OMSF, OSSA, OART, MSFC, MSC, GSFC, LaRC, and Ames RC took part in periodic reviews during the study.

Convair Aerospace Division of General Dynamics was assisted by TRW Systems Group, Redondo Beach, California, in the performance of this contract. Personnel of both companies who contributed to this report are listed below.

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SECTION 1

INTRODUCTION

1.1 OBJECTIVES

The primary objectives of this study are:

a. To define the minimum number of standardized (common) module concepts that will satisfy the NASA Candidate Experiment Program for Manned Space Stations at least cost.

b. To define the module interfaces with other elements of the manned space program such as the space station, space shuttle, ground stations, and the experiments themselves.

c. To define the total experiment module program resource and test requirements including SRT-ART.

1.2 SUMMARY OF RESULTS

The minimum number of common module concepts that will wholly satisfy the NASA Candidate Experiment program at least cost is three, plus a propulsion "slice" and certain experiment-peculiar integration hardware (Figure 1-1).

The experiment modules rely on the space station for operational, maintenance, and logistic support. They are compatible with both expendable and shuttle launch vehicles, and with servicing by shuttle, tug, or directly from the space station.

A total experiment module program cost of approximately $2,319M under the study assumptions is indicated. This total is made up of $838M for experiment module development and production, $806M for experiment equipment, and $675M for interface hardware, experiment integration, launch and flight operations, and program management and support.

1.3 MAJOR GROUND RULES

The following ground rules evolved during the study from the set provided at initiation of effort. They illustrate the reference framework within which results were developed.

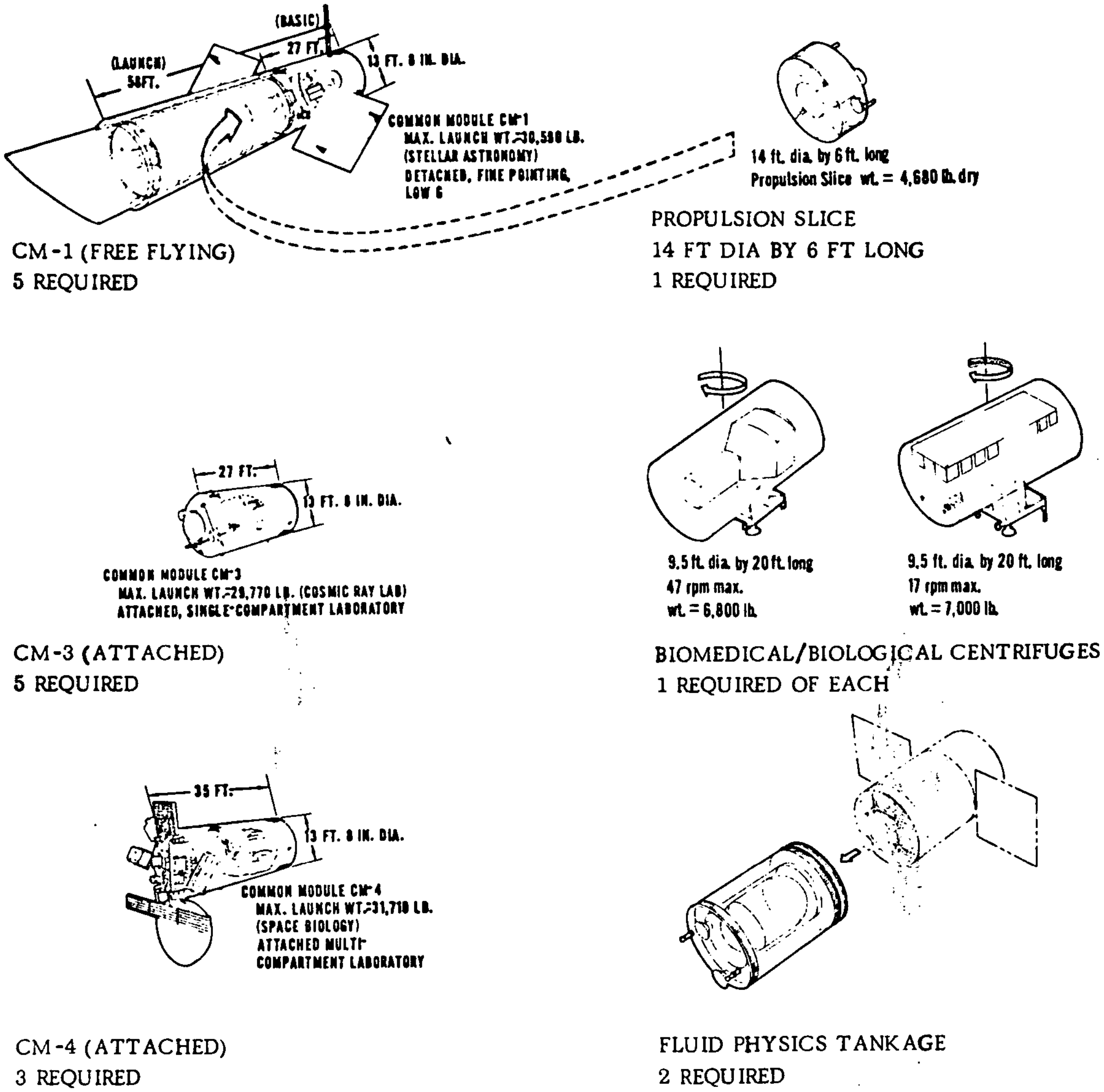


Figure 1-1. Implementation Hardware for Candidate Experiment Program

General

Primary consideration will be given to developing the minimum number of basic module concepts that, through reasonable modification, will be capable of accommodating all candidate experiment groups at least cost.

Experiments

NHB 7150.XX, "Candidate Experiment Program for Manned Space Stations" (Blue Book) will be used as an illustrative program of experiments to be integrated into the Space Station core module or into separately launched experiment/laboratory modules to ensure that the system has the inherent capabilities to support those specific experiments and other experiments not yet identified.

Mission and Operations

a. The modules shall be capable of operating in conjunction with a Space Station in an orbit of 55 degrees inclination and 200 to 300 n.mi. altitude. The modules will not necessarily operate in this altitude range and inclination.

b. For a limited number of experiment groups, the preferred alternative mission of sun-synchronous (polar) orbit at an altitude of 200 n.mi. may be specified.

c. Experiment/laboratory modules may be operated in free-flying, docked, or permanently attached modes and may or may not be manned during their operation. However, all experiment modules operating in detached mode will be unmanned.

d. NASA will specify the operating mode and servicing mode for each experiment group. In some cases, concepts for particular experiment groups may be required for more than one operating and/or servicing mode.

e. Modules that operate in a free-flying mode and do not require the frequent attention of man for operations should have the capability of command and control by a station or logistics spacecraft and from the ground.

f. Modules docked to the Space Station for servicing or operation should be assumed to be docked to a zero gravity station or a non-rotating hub of an artificial gravity station.

g. Unless a space tug is available, all modules designed for detached operation shall have the inherent capability of returning to and docking with the space station.

Configurations

a. Where practical from a payload standpoint, the modules should be compatible with manned logistics systems consisting of Saturn IB-Modified CSM, Titan III-Big Gemini, S-IC/S-IVB-Modified CSM, and S-IC/S-IVB-Big Gemini. Launching the modules in an unmanned mode on these launch vehicles should be considered, and the possibility of transporting the modules in an advanced logistics system should be examined.

b. To the extent practical, experiment/laboratory modules will be designed to be compatible for launch on both expendable and reusable logistics systems.

c. Experiment equipment and module subsystems will be completely assembled/installed on the ground and checked out prior to launch. Assembly in space will be avoided. However, to permit flexibility in updating equipment (and meeting maintenance requirements), designs should allow equipment replacement on the ground or in orbit.

d. The experiment/laboratory modules will be designed for efficient utilization of the support services that the Space Station and the logistics systems can provide. (Where necessary, they will be designed to supply their own services or supplement inadequate services.)

e. To the maximum practical extent, servicing and maintenance of the modules and their experiments will be accomplished without EVA and in a shirtsleeve environment.

f. Modules will be designed for crew servicing, maintenance, and updating in a docked or hangared mode or by on-site repair from a docked tug.

SECTION 2

EXPERIMENTS AND MISSION OPERATIONS

2.1 CANDIDATE EXPERIMENT PROGRAM

The experiment program provided by NASA for use during the study as a basis for development of experiment module concepts is a portion of the Candidate Experiment Program for Manned Space Stations (Blue Book). This program is considered representative of space experiments associated with space station programs in the 1975 to 1985 era. It is defined as being for module and space station design purposes only, and neither the program nor the identified experiments are approved by NASA as planned projects.

This baseline experiment program covers the majority of scientific disciplines concerned with future space research programs:

- Astronomy
- Space Physics
- Space Biology
- Earth Applications
- Biomedicine and Biotechnology
- Materials Science
- Advanced Technology

The experiments within each of these scientific disciplines are further grouped into Functional Program Elements (FPEs). Experiments are grouped into FPEs where characterized by two dominant features: 1) mutually supportive of a particular area of research or investigation, and 2) imposing similar and related demands on space station support systems.

The FPEs are shown in Table 2-1, grouped by discipline. Those FPEs considered as candidates for experiment module application are indicated, as well as those considered as integral to the space station. Table 2-2 summarizes the experiments contained in each FPE.

2.1.1 EXPERIMENT REQUIREMENTS ON MODULES. The governing criteria for development of module concepts were the requirements imposed by the experiments on module design and on module operations. These requirements are generally in four categories:

a. Facility-Type Support. Electrical power, data transmission.

b. Crew Support. Experiment operations and servicing.

c. Environmental Control. Thermal, atmospheric, acceleration, and vibration.

d. Orientation. Direction, accuracy, and stability.

Table 2-1. NASA Candidate Experiment Program

Discipline	FPE No.	Title	Assignment: Module Candidate	Assignment: Station Integral
Astronomy	5.1	Grazing Incidence X-Ray Telescope	X	
	5.2A	Advanced Stellar Astronomy	X	
	5.3A	Advanced Solar Astronomy	X	
	5.4	UV Stellar Survey		X
	5.5	High Energy Stellar Astronomy	X	
	5.21	Infrared Stellar Astronomy		X
Space Physics	5.6	Space Physics Airlock Experiment		X
	5.7	Plasma Physics & Environment Perturbations	X	
	5.8	Cosmic Ray Physics Laboratory	X	
	5.12	Remote Maneuvering Subsatellite	X	
	5.27	Physics & Chemistry Laboratory	X	
Space Biology	5.9	Small Vertebrates (Bio D)	X	
	5.10	Plant Specimens (Bio E)	X	
	5.23	Primates (Bio A)	X	
	5.25	Microbiology (Bio C)		X
	5.26	Invertebrates (Bio F)		X
Earth Application	5.11	Earth Surveys	X	
Biomedicine and Biotechnology	5.13	Biomedical & Behavioral Research	*	X
	5.13C	(Centrifuge)	X	
	5.14	Man/System Integration	*	X
	5.15	Life Support & Protective Systems	*	X
Materials Science	5.16	Materials Science & Processing	X	
Advanced Technology	5.17	Contamination Measurements	X	
	5.18	Exposure Experiments	X	
	5.19	Extended Space Structure Development		±
	5.20	Fluid Physics	X	
	5.22	Component Test & Sensor Calibration	X	
	5.24	MSF Engineering & Operations		X

*To be examined for compatibility with module design concepts.
±Cancelled 5-15-70

By examining the Blue Book definitions of experiment equipment and program requirements, the basic requirements of module subsystems were defined as summarized in Table 2-3.

An analysis was conducted to determine the potential growth or variation that might occur in the requirements of each of the experiment FPEs. These growth projections were then compared to module capabilities, and selected items of growth or variation were incorporated into module design requirements to reduce the sensitivity of modules to changes in experiment requirements, as listed in Table 2-4.

The role of man and the skills required for each FPE are summarized in Table 2-5.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 2-2. Summary of Experiment Program — Module Candidates

FOLDOUT FRAME 3

DISCIPLINE	ASTRONOMY										
FPE NO. TITLE	5.1 X-RAY	5.2A STELLAR	5.3A SOLAR					5.5 HIGH ENERGY STELLAR			
Principal Instrument or Equipment	Telescope 1000 cm^2 3.1 - 62 A X-Ray	Telescope 3 Meter 900 - 10K A UV -VIS - IR	Telescope 1.5 Meter 1300-3000 A UV - VIS	Telescope 0.25 Meter Spectroheliograph XUV	Telescope 0.5 Meter 1 - 24 A X-Ray	Coronograph 1-6 Radii White Light	Coronograph 5-30 Radii White Light	Telescope 0.5 Meter X-Ray	Telescope 0.5 Meter 1.55-124 A X-Ray	Nuclear Spectrometer Gamma Ray	Spark Chamber Nuclear Emulsion Gamma Ray
EXPERIMENTS AND/OR SENSORS 1	Polarimeter	70 mm Video	Spectrograph 3-Range	Image Photo	Spectrograph	Image Film	Image Film	Imaging Video	Spectrograph Point Source	Spectrometer	Photo Emulsions
2	Crystal Spectrometer	225 mm Photo	Hα Monitor Vidicon		Image Photo			Spectrometer	Spectrograph Scan		Spark Chamber
3	Imaging Spectrometer	70 mm Photo	White Light Vidicon		Image Video				Counters (2)		Detectors
4	Detector	Spectrograph Photo	UV Vidicon		Counters						
5	Image TV	Spectrograph Video	Magnetograph								
6		Image TV	Field Image TV								
7											
8											
9											
10											
11											
12											
NOTES											

DISCIPLINE	SPACE PHYSICS			
FPE NO. TITLE	5.7 PLASMA	5.8 COSMIC	5.12 RMS	5.27 PHYS & CHEM
Principal Instrument or Equipment	Wake & Plasma Generators & Sensors	Ionization Spectrograph Detectors & Magnet in Laboratory	Sub-Satellite Sensors	Research Laboratory
EXPERIMENTS AND/OR SENSORS 1	Plasma Wake	Astro-physics	Radio Occultation - Atm Density	Artificial Meteorites
2	Cyclotron Harmonic Resonance	Interaction Physics (H_2 Target)		Ultra Pure Materials
3	Electron Accelerator			Fluid Critical State
4	Wave Particle Interaction			Capillary Dyn-Static
5	Plasma Jet			Bubble Formation
6	Barium Cloud			Free Liquid Drops
7				
8				
9				
10				
11				
12				
NOTES	Uses RMS in FPE 5.12		Used also for FPE 5.7 Plasma Wake	

DISCIPLINE	BIOLOGY			EARTH APP	BIOMED	ADVANCED TECHNOLOGY				
FPE NO. TITLE	5.9 VERTE-BRATES	5.10 PLANTS	5.23 PRIMATES	5.11 SURVEYS	5.13C CENTRIFUGE	5.16 MTLS. SC.	5.17 CONTAM.	5.18 EXPOSURE	5.20 FL. PHYSICS	5.22 COMP. TEST
Principal Instrument or Equipment	Laboratory Specimen Housing & Centrifuge	Laboratory Specimen Housing & Centrifuge	Laboratory & Specimen Housing	Remote Sensors, Calib. Lab Data System	Manned Centrifuge	Research Laboratory	Sensors & Specimens	Sensors & Specimens	Research Laboratory & Test Tanks	Test Chambers
EXPERIMENTS AND/OR SENSORS 1	Cardiovascular (rats)	Response 0-1g (wheat seeds)	Physiology of Chimps	Cameras (2) VIS & IR Multispectra	Walking	Thin Films	Sky Brightness	Meteoroid Composition	Interface Stability	Fuel Cells & Batteries
2	Birth-Growth (rats & other)	Seedling Growth (pea)	Hemodynamic & Metabolic — Monkeys	Infrared Sensors (4)	Work Tasks	Glass Casting	Particle Size	Meteor Flash Analyzer	Boiling Heat Transfer	Liquid-Gas Separation & Measurement
3	Immunization (Marmots)	Morphogenesis (Aribidopsis)		Microwave Devices (5)	Habitability & Hygiene	Spherical Casting	Contamination Monitor	Meteoroid Impact	Capillary	Heat Pipes & Exchangers
4	Birth Growth (Frogs)	Dorso-ventrality		Polarimeter Visible	Tolerance g	Crystal Growth	Optical Samples	Meteoroid Velocity	Condensing Heat Transfer	Air Bearings
5	Reptile Growth (Turtles)	Auxin Reaction (Wheat Seedlings)		UHF Sferics	Re-Entry Simulation	Composites Casting	Thermal Surface Samples	Meteoroid Flux & Velocity	Fluid Properties	Film Processing
6	Gravity to 1g (Rats)	Evolution (Cucumbers)		Absorption Spectrometer	Centrifuge Value	Variable Density Cast.	Contaminant Cloud Composition	Fatigue Samples	Rotating Liquid Globules	Welding
7	Bio-Rythyms (Rats)	Circadian Rythyms (Pinto beans)		Laser Altimeter	Mass Measurement		Dispersal RCS Plume	Spacecraft Surface Samples	Two Phase Flow	Cryogenic Flowmeter
8	Hibernation (Marmots			UV Imager Spectrometer			Charged Contaminant Cloud	Material Bulk Properties	Film Stability	LWIR & MW Radiometers
9				Radar Altimeter Scatterometer					Propellant Transfer	Radiometer Optics
10				Photo Imaging Camera					Long Term Cryogenic Storage	Atmosphere Variability
11				Data Collection					Zero g Combustion	
12									Slush Hydrogen	
NOTES										

Table 2-3. Experiment Requirement Summary

Parameter	X-Ray	Stellar	Solar	High Energy	Plasma Physics	Cosmic Ray	Vertebrates	Plant	Earth Surveys	RMS	Centrifuge	Material Science	Contamination	Exposure	Fluid Physics				Comp. Test	Primates	Phy & Chem
	5.1	5.2A	5.3A	5.5	5.7	5.8	5.9	5.10	5.11	5.12	5.13C	5.16	5.17	5.18	5.20-1	5.20-2	5.20-3	5.20-4	5.22	5.23	5.27
Orientation	Stellar	Stellar	Solar	Stellar	-	Zenith	-	-	Earth	-	-	-	-	Earth	-	-	-	-	Earth(1)	-	-
Pointing																					
Accuracy (± $\widehat{sec}$)	120	10	2.5	15	-	(9)	-	-	1080	-	-	-	-	-	-	-	-	-	30	-	-
Stability ($\widehat{sec}$/exposure)	1.0	0.005	0.01	1.0	-	-	-	-	108	-	-	-	-	-	-	-	-	-	7.2	-	-
Acceleration Constraints (g)	-	-	-	-	-	-	10^{-3}	10^{-5}	-	-	-	10^{-3}	-	-	10^{-4}	(Sustained accel. at 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6})			10^{-2}	10^{-3}	10^{-6}
Experiment Equipment																					
Weight (pounds)	3300	8685 (10)	6875 (10)	7800	1800	34180	5747	2599	4600	3200	1720	5580(4) (10)	850	400	785	5141	3460	5252	1650	4500	6220
Data (Also see Table 2-3)																					
Digital Rate (kbps)	8	8000	5000	10	80	10	10	10	26,400	-	25	1	63	8.4	1	5.78	6	6	20	200	1
Analog Bandwidth (kHz)	-	-	-	-	10	-	-	-	3600	-	-	.001	-	0.1	-	-	-	-	-	-	-
TV Channels	1	1	1 3 @ 1.3 MHz	1	1	1	2	1	1		1	2	2	-	1	6 (8)	1	2	1	1	1
Film Required	-	Yes	Yes	(Emulsions)	Yes	(Emulsions)	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electrical Power - Average (kW)	0.19	0.74	0.50	0.51	1.28	3.1	1.0	0.35	1.04	-	0.25	2.0	0.4	0.143	0.4	1.0	1.4	0.17	1.0	2.6	1.6
- Peak (kW)	0.36	1.25 (10)	0.85	0.65	1.9	4.4	1.75	0.35	6.9	-	0.25	5.0	0.5	0.26	1.1	1.4	4.0	1.2	1.8	3.3	2.3
Operating Environment																					
Pressure (psia)	0	0	0	0	0	14.7	14.7	14.7	14.7	-	14.7	14.7	0	0	14.7	0- 14.7	0	0	0 14.7	14.7	14.7
Temperature (°F)	(5)(6)	(6)	(6)	(5)(6)	-		70	70	70	-	70	70(7)	Space	Space	70	70	-	-	(5)	70	70(7)
Temperature Tolerance (°F)	-	-	-	-	-	(5)	±5	±5	±5	-	±5	±5	-	-	±5	±5	-	-	-	±5	±5
Operating Metabolic Load (Btu/hr)	-	-	-	-	-	-	700(2)	700(2)	-	-	500(3)	-	-	-	-	-	-	-	-	700	-
Cryogenic Supply Required (LB/MO)	125	-	-	-	-	250	-	-	20	-	-	10	-	-	-	-	-	250	980	-	133
Contamination Sensitive	Yes	Yes	Yes	Yes	-	-	-	-	Yes	-	-	-	Req'd	Yes	-	-	-	-	Yes	-	-
Radiation Sensitive (Below Personnel Level)	Yes	-	Yes	Yes	-	Yes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

NOTES:
(1) Two sensor experiments require view of earth for short periods (15 min).
(2) EC/LS system for specimens is provided with experiment. Value shown is for scientist crew EC/LS.
(3) EC/LS system on centrifuge.
(4) Estimated weight of lab equipment.
(5) Contains sensors which are cryogenically cooled.
(6) Contains temperature critical sensors.
(7) Temperature control varies with each experiment.
(8) Reduced bandwidth is acceptable.
(9) Attitude known within ±2 deg.
(10) Growth projection incorporated.

Table 2-4. Experiment Revisions and Growth Items Incorporated into Experiment Requirements

FPE	Title	Change
5.2A	Stellar	Provide for observation on sunlit side of orbit, and capability for polarity measurement. Mirror weight increased from 1700 to 4000 lb.
5.3A	Solar	Boresight group of point-target instruments. Photoheliograph weight increased from 3200 lb to 4000 lb. Add 3 vidicon cameras, and provisions for 1 magnetograph.
5.7	Plasma Physics	Provide for centralized laboratory for experimentation, test conduction and data reduction.
5.8	Cosmic Ray	Provide growth version to include astrophysics experiments only, with dual magnet (no torque), and total absorption detector replacing ionization spectrograph.
5.9/10/23	Biology Lab.	Include growth provisions for FPE 5.25 (Microbiology) and FPE 5.26 (Invertebrates) Provide for shuttle compatible centrifuge with manned access.
5.13C	Centrifuge	Provide for shuttle compatible centrifuge.
5.16	Materials Science	Include growth provisions for analysis equipment and furnace.

Table 2-5. Summary of Crew Requirements — Experiment Modules

FPE NO.	TITLE	Type of Experiment: Man Conducted	Type of Experiment: Man Serviced	MAX. NO. OF CREW MEMBERS AT ANY ONE TIME	NORMAL OPERATING MODE: Attached	NORMAL OPERATING MODE: Detached	NOMINAL DURATION & FREQUENCY OF MANNING	REMARKS/DUTIES
5.1	X-Ray Astronomy		X	2		X	2-3 Days - every 60 days.	Routine equip. maint., refuel, resupply cryogenics, update sensors (1/year).
5.2A	3-Meter Telescope		X	2		X	2-3 Days - every 60 days.	Refuel, update sensors (1/year).
5.3A	Solar Astronomy		X	2		X	2-3 Days - every 60 days.	Replace film, refuel, update sensors, change gratings (1/year).
5.5	Hi-Energy Astronomy		X	2		X	2-3 Days - every 30 days.	Routine maint., refuel, resupply cryogenics, update sensors, replace emulsions.
5.7	Plasma Physics	X		2	X		5-10 Days per experiment · 5 times/yr.	Operate RMS and sensors, monitor data, calibrate and service instrumentation.
5.8	Cosmic Ray		X	2	X		1 Man continuous 8 hrs/day: 2 man setup 4 hrs/90 days.	Monitor data 8 hrs/day. Revise experiment. Service dewar, change emulsions (1/3 days).
5.9 5.10	Space Biology	X		2	X		2 Men continuous for 8 hrs/day.	Attend specimens, conduct & monitor experiment, and load/unload biocentrifuge.
5.11	Earth Surveys	X		2	X		2 Men continuous for 8 hrs/day.	Operate sensors, monitor data, calib. & service instr.
5.12	RMS Hangar (see 5.7)	X		2	X		(Same operation as in 5.7)	Same man) Deploy/retrieve, service RMS, waste disposal.
5.13C	Centrifuge	X		2	X		2 Men	Operate centrifuge, monitor subject, act as subject.
5.16	Matls. Process Lab	X		2	X		2 Men continuous for 8 hrs/day.	Prepare, conduct, monitor experiment, analyze specimens and attend to free-flying modules.
5.17	Contamination		X	1 + 1	Suitcase X		2 Men (1 + 1 EVA) for 4 days every 60 days.	Measure samples, replace, monitor automated instr.
5.18	Exposure		X	1 + 1		Suitcase X	2 Men (1 + 1 EVA) " " "	Measure samples, replace, monitor automated instr.
5.20	Fluid Physics	X		2	X	X	2 Men continuous for 8 hrs/day.	Prepare & conduct experiment, attend to free-flying module, film replacement.
5.22	Comp. Test/Sensor	X		2	X		1 to 2 Men continuous 8 hrs/day.	Set up and conduct experiment, maintain test equipment.
5.23	Primates (Bio A)	X		2	X		(Same as 5.9 and 5.10)	Attend specimens, conduct experiments.
5.27	Physics & Chem.	X		2	X	X	2 Men continuous for 8 hrs/day.	Set up and conduct experiments, attend to free-flying module (5.20) when used for 5.27 experiments.

A key factor in module design was to determine the operating mode to meet experiment objectives. The two basic operating modes available were: 1) attached to the space station, and 2) free-flying. Modules designed to be operated in the attached mode receive necessary power, data handling and transmission, life support, and other support from the space station. Free-flying modules must be self-sustaining and must have orbital maneuvering flight capabilities. Therefore, the attached mode is preferable except where experiment environment dictates a free-flying mode.

Implementation of the experiment program must provide the environment required for successful experiment operations. In most cases, the environment can be provided with the module attached to the space station throughout the experiment program. For certain experiments, however, a free-flying mode is necessary to isolate the experiment from space-station-originated environmental conditions. The module returns to the station only for servicing of the experiment and supporting subsystems.

Environment requirements of the experiments are compared to the projected conditions for the space station in Table 2-6, and the operating mode selected for each FPE is listed.

2.2 MISSION OPERATIONS

The experiment program will be conducted in conjunction with a space station in low earth orbit (270-n. mi. altitude and 55-degree inclination).

Module operating requirements are based on the experiment modules being a part of the total space station system (see Figure 2-1) and, as such, deriving significant support from the other elements and being constrained to be compatible with these support elements. Modules are delivered to orbit by the earth-to-orbit shuttle (or expendable launch vehicles). Attached modules dock to the space station and remain docked for their normal mission life.

Free-flying modules dock to the station for initial activation/calibration, free-fly for experiment operations, and periodically return to the station for servicing. During the free-flying mode, experiment and module operations are controlled by the space station, and experiment data and module subsystem status are transmitted back to the station for processing, action, and retransmittal to ground.

Modules are also to be capable of being serviced while in the free-flying mode by the shuttle or other manned service vehicles.

Experiment modules designed to implement the experiment program must be compatible with two major mission operations related to the space station:

a. Launch and rendezvous with the space station, using either expendable launch vehicles or the space shuttle.

Table 2-6. Selection of Operating Mode

FPE	Title	Experiment	Environmental Requirements: Accel. Ambient	Accel. Induced	Stability $\widehat{sec}$/sec.	Viewing	Contamination	Radiation	Basis for Selected Mode	Selected Mode of Operation
5.1	X-Ray	---	---	---	1.0	Sphere	Sensitive	Sensitive	Contamination & Radiation, viewing	Detached
5.2A	3-M Stellar	---	---	---	0.005	Sphere	Sensitive	--	Stability & Control, viewing, contam.	Detached
5.3A	Solar	1.5-M UV-Vis.	---	---	0.01	Solar	Sensitive	---	Stability & Control, contamination	Detached
		.5-M X-Ray	---	---	0.5		Sensitive	---	Contamination	Detached
		Spectro. Corona.	---	---	0.1		Sensitive	Sensitive	Contamination & Radiation, viewing	Detached
5.5	High Energy	X-Ray	---	---	1.0	Sphere	Sensitive	Sensitive	Contamination & Radiation, viewing	Detached
		Gamma	---	---	3 $\widehat{min}$/exp.		---	Sensitive	Radiation	Detached
5.7	Plasma	---	---	---	---	---	---	---	Experiment Operation	Attached
5.8	Cosmic Ray	Control	---	---	---	---	---	---	Station Compatible	Attached
		Sensors	---	---	---	Zenith	---	Sensitive	Station Compatible	Attached
5.9	Vertebrates (Bio D)	"0" g	$\leq 10^{-3}$g	---	---	---	---	Sensitive	Station Compatible (1)	Attached
		Variable g	---	.2 to 1 g	---	---	---	Sensitive	Station Compatible (1)	Attached - Centrifuge
5.10	Plants (Bio E)	"0" g	$\leq 10^{-5}$g	---	---	---	---	Sensitive	Station Compatible (1)	Attached - isolated g
		Variable g	---	.2 to 1 g	---	---	---	Sensitive	Station Compatible (1)	Attached - Centrifuge
5.11	Earth Surveys	---	---	---	108.	Earth	Sensitive	---	Protect from Contamination	Attached
5.12	RMS	---	---	---	---	---	---	---	Experiment Operation (2)	Attached/Detached
5.13C	Centrifuge	---	---	0 to 7 g	---	---	---	---	Station Compatible	Attached - Centrifuge
5.16	Materials Processing	---	$\leq 10^{-3}$ g	---	---	---	---	---	Station Compatible	Attached
5.17	Contamination	---	---	---	---	---	Required	---	Contamination Required	Attached - *
5.18	Exposure	---	---	---	---	---	Sensitive	Sensitive	Contamination & Radiation	Detached - *
5.20	Fluid Physics	"0" g	$\leq 10^{-4}$g	---	---	---	---	---	Station Compatible	Attached
	Fluid Physics	10^{-3} to 10^{-6} g	---	10^{-3} to 10^{-6}g	---	---	---	---	Acceleration Required	Detached - Propelled
5.22	Component Test	---	---		7.2	Earth	Sensitive	---	Protect From Contamination	Attached
5.23	Primates (Bio A)	---	---	---	---	---	---	---	Station Compatible	Attached
5.27	Physics & Chemistry	---	$\leq 10^{-4}$g		---	---	---	---	Station Compatible	Attached
	Space Station Ambient		10^{-3} to 10^{-5} g		18 $\widehat{sec}$.	Earth or Inertial Oriented	Source of Potential Gases & Solids	Power Generator		

*Suitcase experiments

(1) Assumed located at adequate distance from power generator.
(2) Housed in attached mode.

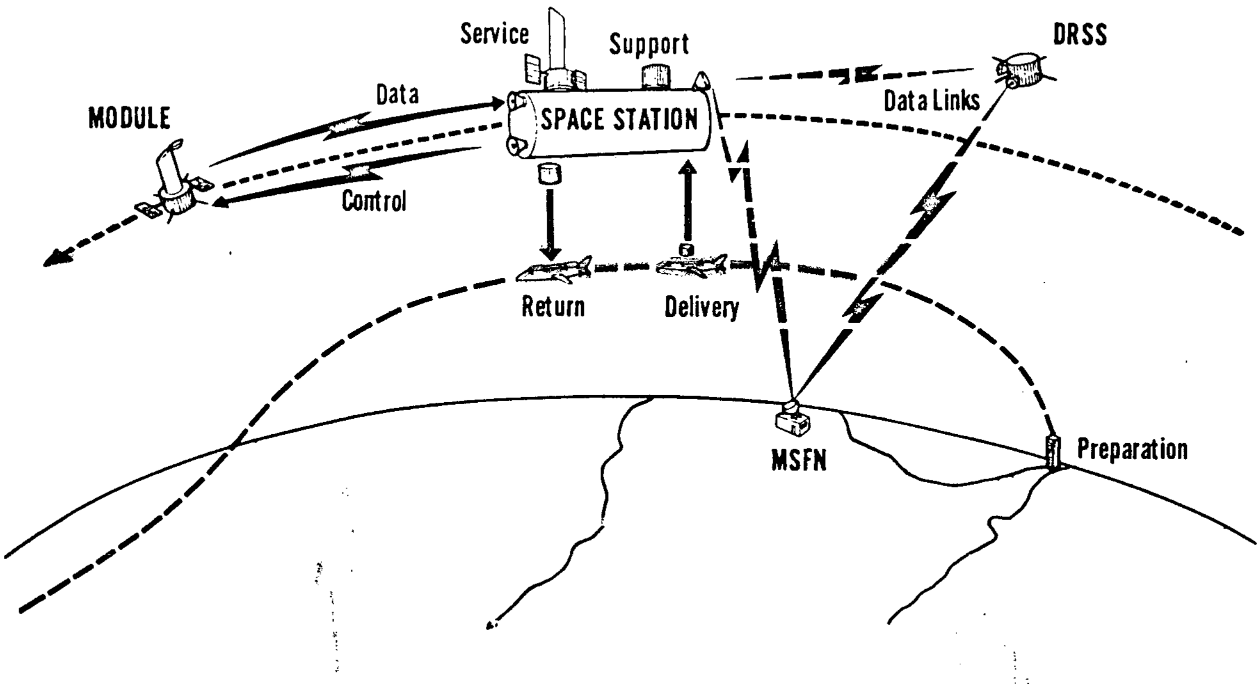


Figure 2-1. Experiment Module Operations

b. Operating co-orbitally with the space station in either an attached or free-flying mode.

2.2.1 LAUNCH OPERATIONS. Experiment modules are by study ground rules to be compatible with both space shuttle and expendable launch vehicles.

Shuttle launch vehicle payload capability is ground ruled at 25,000 pounds delivered to space station 270 n.mi. circular orbit, or approximately 33,000 pounds delivered to a 100 x 270 n.mi. elliptical orbit.

Expendable launch vehicle capabilities for total payload to 270 n.mi. at 55 degrees inclination, less allowances for jettisonable fairings, together with limits on payload length for 15-foot-diameter modules for 95 percent launch probability are:

Launch Vehicle	Payload Capability - Pounds 270 n.mi. Circular	100 x 270 n.mi. Elliptical	Payload Cylinder Length (ft)
Titan IIIC	12,000	20,000	53
Titan IIIF	18,000	28,000	46
Saturn IB	24,000	34,000	65

Rendezvous and docking to the space station is then accomplished by the module system for both attached and free-flying experiment modules.

Planning data for three classes of expendable launch vehicles and for shuttle vehicles necessary to support the experiment module program based on the interim module designs are given in Table 2-7.

Shuttle expendable launch vehicle and delivery capabilities are compared to module weight and envelope characteristics in Figures 2-2 and 2-3.

Review of Figure 2-2 shows that a shuttle payload capability of 25,000 pounds to circular orbit will meet all module requirements if elliptical orbit delivery is used for payloads over 25,000 pounds. Review of Figure 2-3 shows that all experiment module payloads can be carried by either Titan IIIF or Saturn IB expendable launch vehicles.

Table 2-7. Experiment Module — Launch Vehicle Requirements

Common Module			FPE	Title	Shuttle Requirements 25k Payload	Expendable L/V(3) Requirements		
1	3	4				T-IIIC 20K P/L	T-IIIF 28K P/L	S-IB 34K P/L
x			5.1	X-Ray	1		1	
x			5.2A	Stellar	1			1 (4)
x			5.3A	Solar	1		1	
x			5.5	High Energy	1		1	
	x		5.7/5.2	Plasma Physics	1		1	
	x		5.8	Cosmic Ray	1			1 (4)
Experiment Unique			5.8	Cosmic Ray	1 (E)		2 (E)	
		x	5.9/10/23	Space Biology	1(1)			1 (4)
		x	5.11A	Earth Surveys	1		1	
Experiment Unique			5.13C	Centrifuge	1 (E)	1 (E)		
	x		5.16	Materials Science	1		1	
	x		5.20-1	Fluid Physics	1	1		
x			-2(2)	Fluid Physics	1			1 (4)
Experiment Unique			-3(2)	Fluid Physics	1 (E)	1 (E)		
Experiment Unique			-4(2)	Fluid Physics	1 (E)	1 (E)		
		x	5.22	Components Test	1		1	
	x		5.27	Physics & Chemistry	1		1	
				TOTALS	13 Module 4 (E)	1 Module 3 (E)	8 Module 2 (E)	4 Module

LEGEND:
(E) Indicates experiment unique launch.

NOTES:
(1) Centrifuge is launched in combination with module.
(2) One propulsion slice is included. The same propulsion slice is used for the -2, -3, -4 experiment. The same CM1-1 module is also reused. Experiments are exchanged on-orbit.
(3) Based on extrapolated L/V performance data in References 3-1.1 and 3-1.2
(4) Alternate launch vehicle is TIIIF to interim altitude with module providing 4ΔV to final altitude.

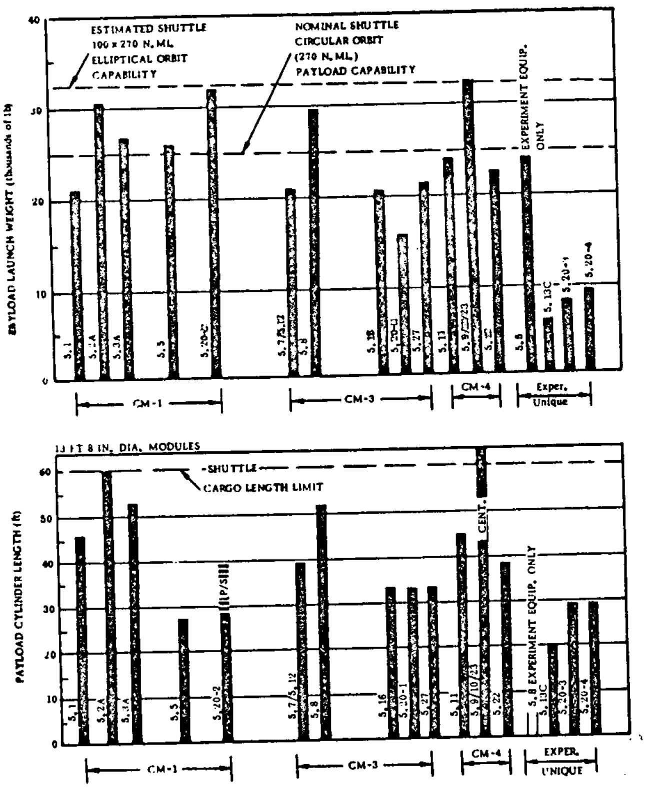


Figure 2-2. Shuttle Payload Sensitivity

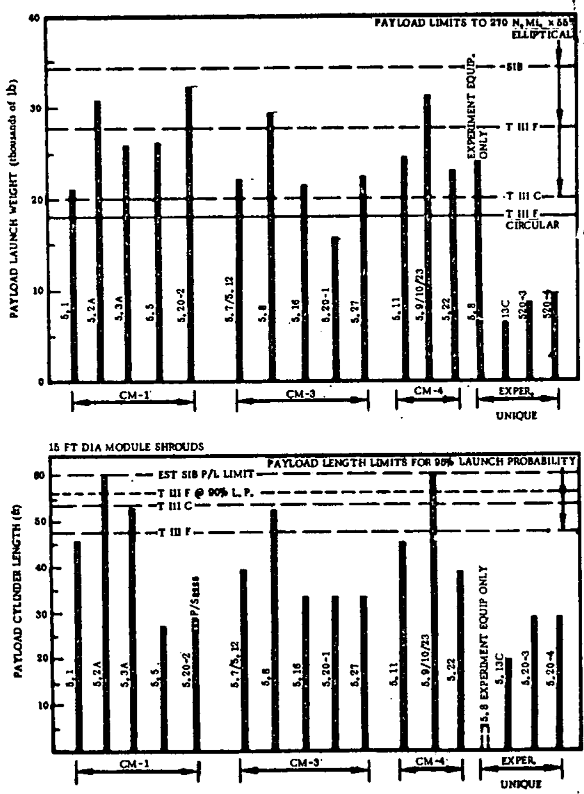


Figure 2-3. Expendable Launch Vehicle Payload Sensitivity

2.2.2 ON-ORBIT OPERATIONS. Module Operating criteria for conducting the experiment program in conjunction with a space station to which modules are permanently docked (or periodically docked for servicing in the case of free-flying modules) include:

a. Functional requirements of modules.

b. Orbital maintenance requirements and stationkeeping techniques for free-flying modules operating in the vicinity of the space station.

c. Techniques and performance criteria for experiments requiring constant low g levels over extended time periods.

Experiment and mission requirements and ground rules were analyzed to determine operating functions and requirements, and to allocate them to either the experiment module or to other primary program elements.

Typical operating sequences and functions for free-flying modules are shown in Figure 2-4. The elements among which operating functions are allocated are experiment modules, space station, logistics, and ground systems.

2.2.2.1 Orbit Maintenance and Stationkeeping. A body in low earth orbit will experience orbit decay due to aerodynamic drag, which is a function of atmospheric density and the ballistic coefficient of the body. Relative to a drag-free body, the body experiencing drag follows a path of lower radius and higher angular velocity and will soon pass and precede the drag-free body in orbit. Stationkeeping then consists of applying a velocity change (ΔV) to the drag body to execute a Hohmann transfer to its original, or a higher, orbit as shown in Figure 2-5. Three basic stationkeeping methods are shown:

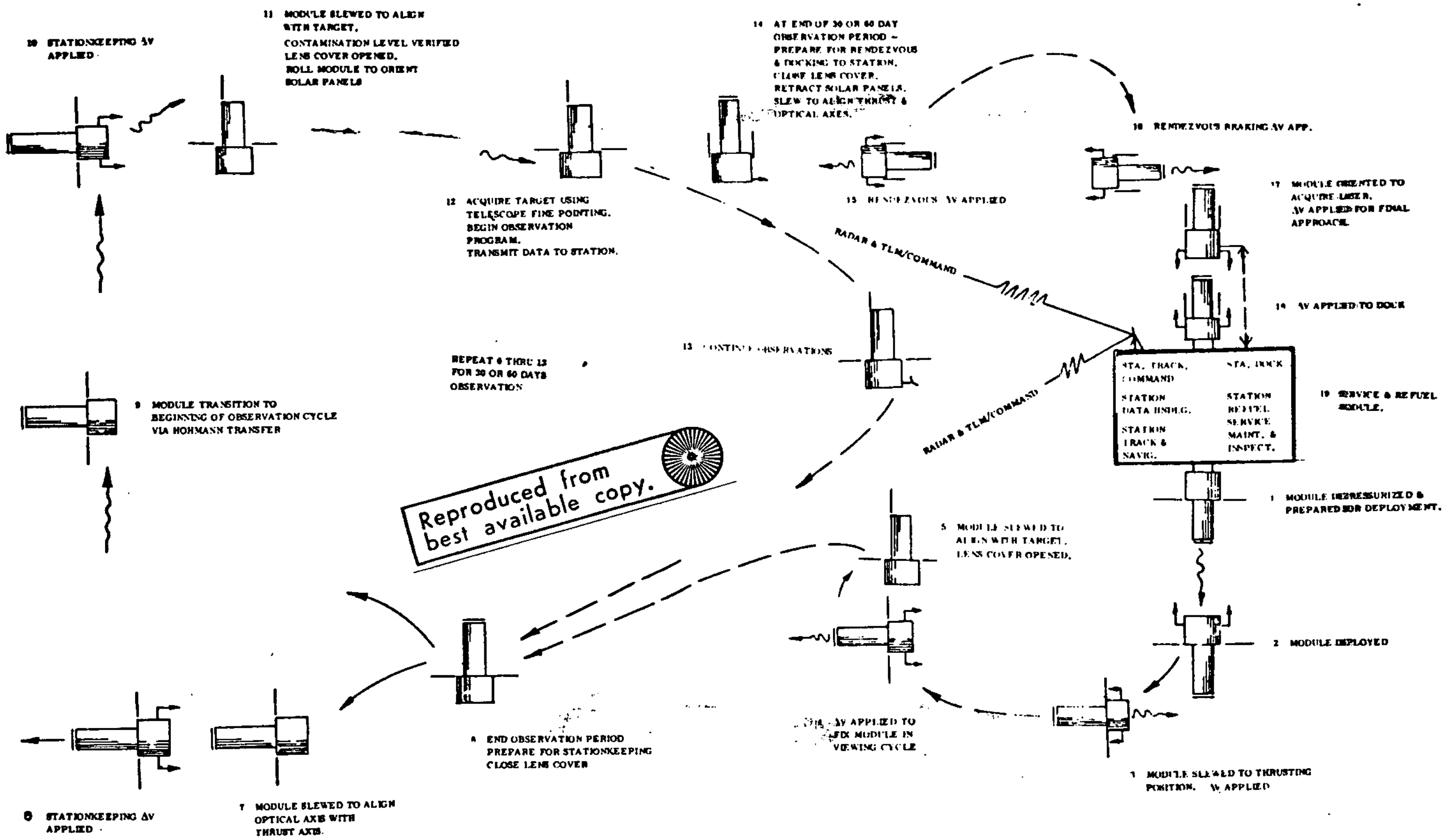
a. Transferring to an orbit sufficiently high to cause the module to pass behind and below the station.

b. Conducting stationkeeping behind the station by boosting the module to a higher altitude behind the station.

c. Conducting stationkeeping ahead of the station by boosting the module to an altitude that will result in decay to the station altitude ahead of the station position.

In each case, the average altitude of the decay transfer loop is the same as that of the station; ΔV requirements are about equal. The length of the loop is limited by communications range.

2.2.2.2 Selection of Stationkeeping Method. Encircling the station provides the longest periods between ΔV for a given communications distance, but presents the station and other modules as potential occulting bodies for astronomy modules. Stationkeeping behind or in front of the station appear to be about equally preferable except for the contamination potential, which appears to be least in front of the station.



MISSION PHASE	ΔV (FPS)
RENDEZVOUS & DOCK (INITIAL)	85
UNDOCK	10
DEPLOYMENT	15
STATIONKEEPING	4
RETURN	15
DOCK	20

Figure 2-4. Typical Astronomy Module Mission Profile

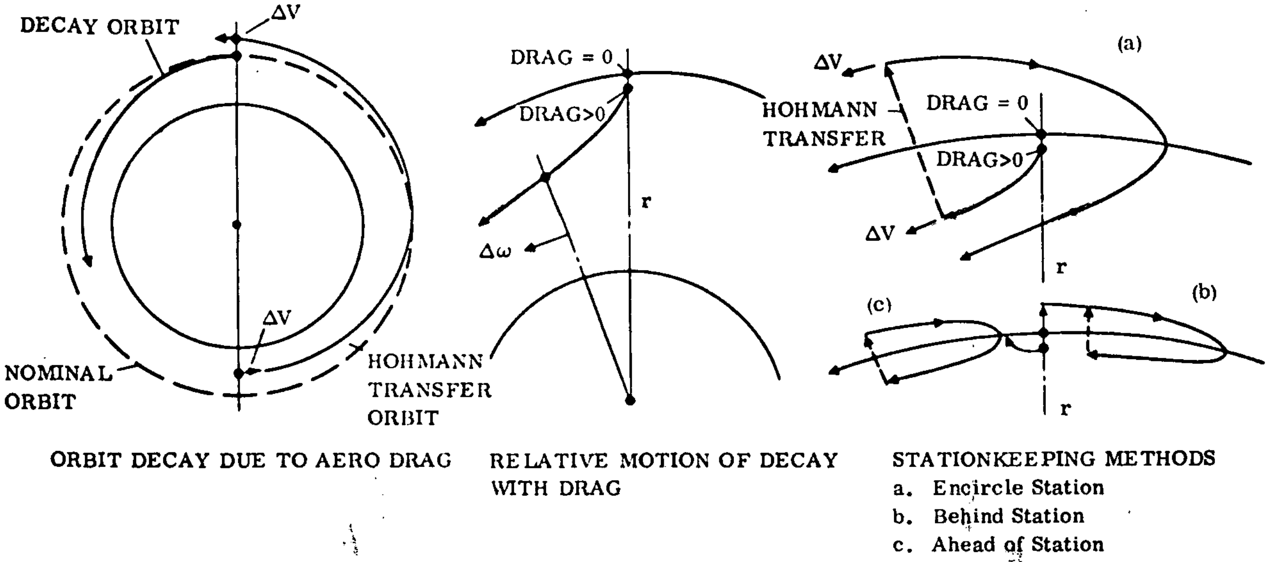


Figure 2-5. Orbital Motion and Stationkeeping

The stationkeeping method selected for astronomy modules for the baseline case is based on experiment considerations and is the one in which astronomy modules are kept in a loop that precedes the station in orbit. This method reduces the potential of occulting by the station and the potential of degradation of viewing due to any contaminants trailing the station.

Considerations for stationkeeping of free-flying laboratory sections are more operations-oriented and include flight patterns and durations, traffic control around station, and avoiding presenting an occulting body to viewing instruments such as astronomy modules.

2.2.2.3 Stationkeeping Performance Requirements

a. Module Drag Offset. The module performance required to offset drag is dependent on the atmosphere and the module ballistic coefficient. The nominal density at a given altitude is a strong function of solar activity, which varies on a solar cycle with a period of about 11 years. Perturbations in density include a strong diurnal bulge effect due to daily solar heating and smaller perturbations due to many lesser effects.

The average ballistic coefficient (β) for the astronomy modules as currently designed is about 20 psf. At space station altitudes, this will require approximately 0.33 fps ΔV per day for years of highest atmospheric density (CIRA Model 10), about 0.1 fps for mean density (CIRA Model 5) and about 0.002 fps for least density (CIRA Model 1). Propellant requirements average about 3 to 4 pounds per fps ΔV for these modules, totaling about 1 pound per day for the worst case at space station altitudes. The modules are currently designed to provide orbit maintenance using their integral RCS.

b. Stationkeeping Cycles. Application of the orbit-maintenance ΔV to recover the lost altitude of the module in a manner to keep it within close proximity of the space station constitutes the stationkeeping function.

The amount of time lost to observations as a result of stationkeeping maneuvers is a direct function of the frequency at which stationkeeping ΔV must be applied. It therefore is very desirable to minimize this frequency.

The frequency of ΔV application is determined by the allowable distance between the module and station. The primary limit is communication system requirements. The module baseline operating range of 500 n. mi. will result in a stationkeeping cycle time of about 30 days, with communication power of 5 watts, as shown in Figure 2-6.

The ΔV requirements for these modules in the worst-case atmosphere are shown in Table 2-8 for orbit maintenance and deployment, return, and docking to the space station. The cycle shown is based on maximum communication distance of 500 n. mi. from the space station.

2.2.2.4 On-orbit Transportation. Experiment modules must be either self-propelled or be transported while on-orbit to:

a. Deliver the module from the launch vehicle to the space station.

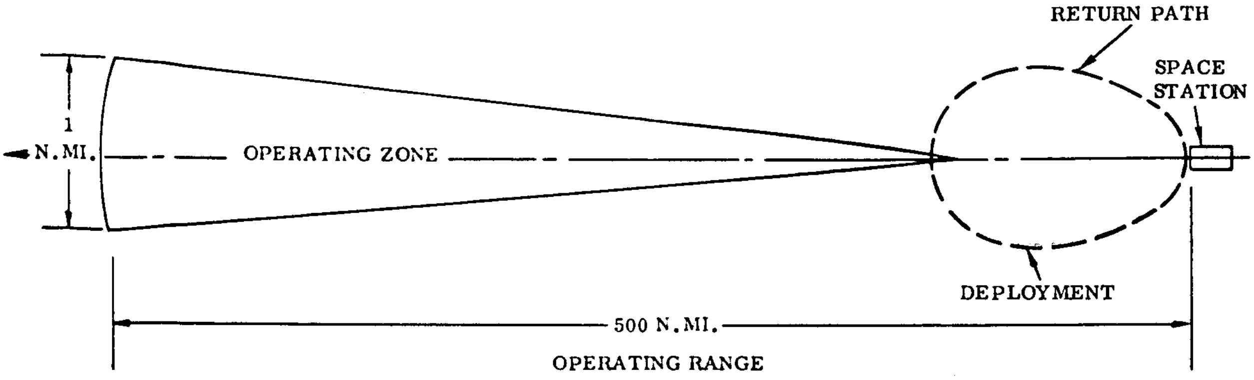
b. Relocate experiment modules from one space station docking port to another.

c. Deliver modules to free-flight orbits and return modules to the space station.

d. Provide stationkeeping velocity increments for maintenance of free-flight orbits.

Experiment module baseline designs have propulsive capability integral to the modules. To evaluate the effectiveness of these designs, modules with integral propulsion were compared with modules with no, or limited, propulsive capability.

The modules with reduced propulsion capability require auxiliary vehicles (i.e., space tug type spacecraft or transporters) for on-orbit module transportation. Transportation concepts were compared on the basis of cost, experiment growth potential, impact on space station, funding, flexibility, and technical risk.



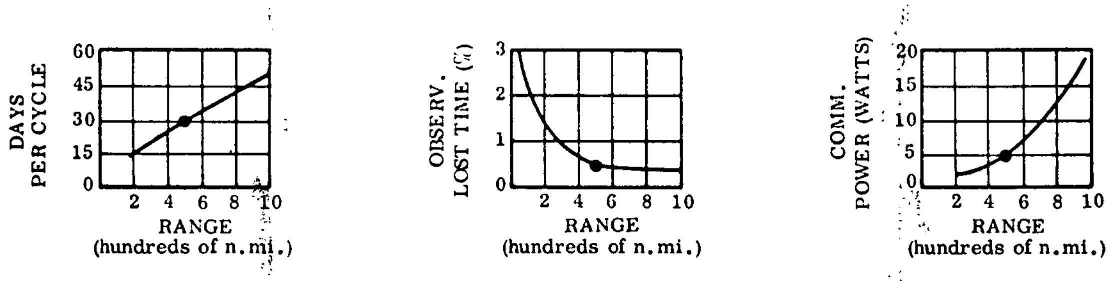


Figure 2-6. Astronomy Module Relative Orbit Paths

Table 2-8. Astronomy Module Mission Cycle ΔV Requirements

PARAMETER	FPE 5.1 X-RAY	5.2 A STELLAR	5.3A SOLAR	5.5 HIGH ENERGY
Experiment Module β (lb/ft^2)	20	16	19	25
Number of Days Per Service Cycle	60	60	30	60
Maximum Number of Days Per Stationkeeping Cycle	35	31.4	34.2	39.2
Number of Stationkeeping Cycles Per Service Cycle	2	2	2	2
ΔV Per Stationkeeping Cycle (fps)	2.2	2.8	2.4	1.8
Undocking ΔV	10.0 fps	10.0 fps	10.0 fps	10.0 fps
Deployment ΔV	8.6	8.6	8.6	8.6
Out-of-Plane ΔV	6.0	6.0	6.0	6.0
Stationkeeping ΔV Per Service Cycle	4.4	5.6	2.4	3.6
Return ΔV	8.6	8.6	8.6	8.6
Out-of-Plane ΔV	6.0	6.0	6.0	6.0
Docking ΔV	20.0	20.0	20.0	20.0
Total ΔV Per Service Cycle	63.6 fps	64.8 fps	61.6 fps	62.8 fps

Study conclusions for the use of a transporter as part of the experiment module program in lieu of integral module propulsion are:

a. There is no conclusive cost advantage to the use of a transporter for experiment module operations, as shown in Table 2-9.

b. Transporter use may be advantageous for noncosted factors:

   1. Reduction in contamination through in-situ servicing.

   2. Growth missions to other orbits.

c. Maximum program flexibility is achieved with modules capable of operations independent of a transporter.

2.2.2.5 Special Experiment Flight Missions. One of the experiment FPEs contains experiments selected for operation in the free-flying mode:

FPE 5.20, Fluid Physics, is operated detached to achieve the constant low acceleration levels (10^{-6} to 10^{-3} g) required to meet experiment objectives.

This is accomplished by linear acceleration of the experiments using propulsive methods. In general, the use of gravity-gradient methods is ruled out because of unacceptable coriolis acceleration effects.

2.3 EXPERIMENT MODULE INTERFACES

2.3.1 SPACE STATION INTERFACE. Experiment modules have been designed assuming that the necessary support is provided by the space station and that the station can accommodate necessary loads, docking ports, and certain torques imposed on the station by the modules.

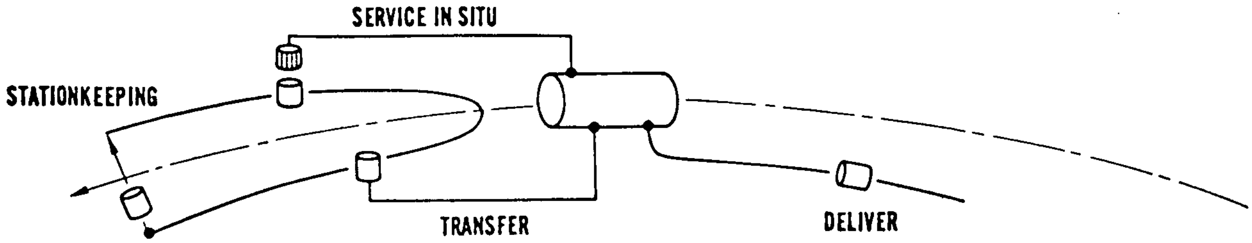
Maximum values for any single attached or free-flying module shown in Table 2-10 represent the limiting loads expected. A single module would not impose all the worst-case conditions simultaneously.

Propellant loading is required for five free-flying modules.

Two attached experiment-unique centrifuges could contribute gyroscopic torque loads during a space station angular maneuver. Magnetic torque generated by FPE 5.8, Cosmic Ray experiment, can be de-coupled through a gimballed joint, although the growth projection for this FPE uses a dual, torque compensating, magnet.

Suitcase experiments are those carry-on type experiments that do not require separate modules. These are: FPE 5.17 (Contamination Measurements) and FPE 5.18 (Exposure experiments). Experiments in this category are accommodated by either attached or free-flying modules or by the space station, depending on the experiment requirements.

Table 2-9. Transporter Trade Study



TYPE MODULE	COST ITEM	Δ COST FROM MODULE PROPULSION ($M)	
		MANNED TRANSPORTER	UNMANNED TRANSPORTER
FREE-FLYING	MODULE SUBSYSTEMS	− 11.2	− 11.2
	DOCKING ATTACHMENTS	+ 16.4	+ 16.4
	TRANSPORTER RDT&E, PROD.	+102.0	+ 44.7
	10-YR. OPER (CREW & PROP.)	+ 30.5	+ 61.3
	TOTAL	+137.7	+111.2
ATTACHED	MODULE SUBSYSTEMS	− 76.2	− 76.2
	DOCKING ATTACHMENTS	+ 7.0	+ 7.0
	TRANSPORTER RDT&E & PROD.	+ 88.4	+ 31.1
	10-YR. OPER (CREW & PROP.)	+ 16.5	+ 15.5
	TOTAL	+ 35.7	− 22.6

Table 2-10. Space Station Interface Summary

Item	Maximum Values of Attached Modules	Maximum Values of Detached Module
Thermal	None	
Electrical - Peak Average	7.0 kW 5.2 kW	
Data:		
Hardline Digital Data (Rate)	26.4×10^6 bPS	
Hardline TV/Analog (Bandwidth)	4×10^6 Hz	
RF Digital Data (Rate)		1×10^6 bPS
RF TV/Analog (Bandwidth)		0.20×10^6 Hz
Telemetry, Tracking and Command	S-Band	S-Band
Magnetic Torque	None	
Pointing	Nadir ± 0.25 deg	

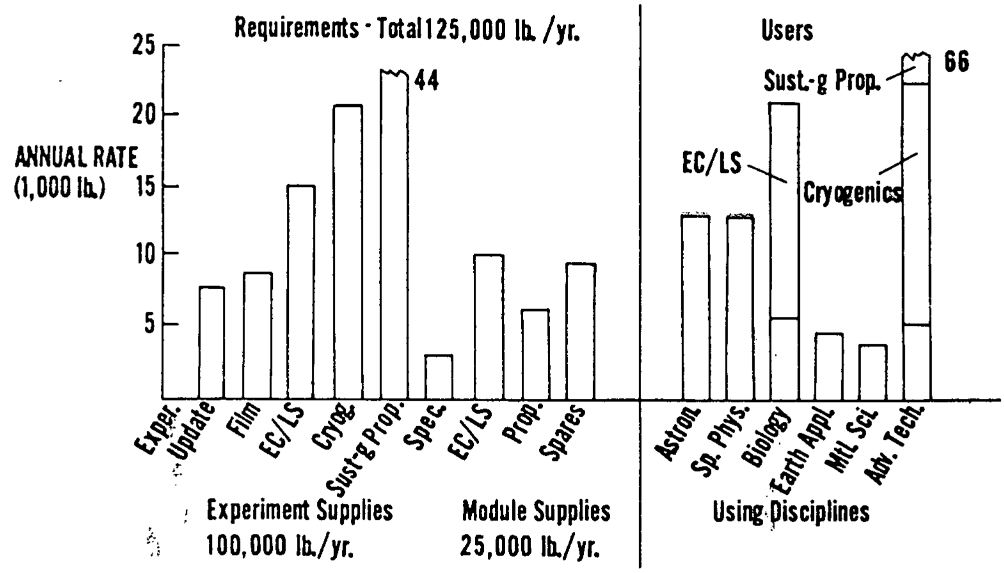


Figure 2-7. Preliminary Logistics to Orbit

2.3.2 LOGISTIC SYSTEM INTERFACES. Figure 2-7 shows the logistics items to be delivered to orbiting experiment modules, including updated experiment apparatus; spares needed to replace failed module equipment; propellants consumed in station-keeping, maneuvering, and docking; and other expendables such as film, test fluids, batteries, and pressurizing gases.

2.4 ENVIRONMENT

Experiment modules must survive launch by either re-usable or expendable launch vehicles, and operate on-orbit for periods up to ten years. The environments that must be considered include:

a. Launch Environment
   1. Load factors
   2. Acoustic
   3. Thermal

b. On Orbit Environment
   1. Rediation
   2. Meteoroid
   3. Contamination

Sensitivity of the various FPEs to radiation environment is shown in Table 2-11, being largely those experiments containing films, emulsions, or sensitive instruments.

Contamination will be a consideration for all optical experiments, and will influence selection of attached or free-flying operating mode, and selection of propellants for RCS systems.

Table 2-11. Radiation Sensitivity by FPE

FPE/TITLE	RADIATION SENSITIVE ITEM			
	MAN			
	PERIODIC SERVICING	SUSTAINED OPERATION	FILM	OTHER
5.1 X-Ray	X	—	—	X-Ray Instruments
5.2 Stellar	X	—	X	Photometer
5.3 Solar	X	—	X	X-Ray Telescope, Misc. Instr.
5.5 High Energy	X	—	—	X and γ-Ray Instruments, Emulsions
5.7/12 Plasma Physics	—	X	—	------
5.8 Cosmic Ray	—	X	X	Emulsions, Cosmic Ray Detectors and Multipliers
5.9 Small Vertebrates	—	X	X	Small Vertebrates
5.10 Plants	—	X	X	Plants
5.11 Earth Surveys	—	X	X	IR Instruments
5.16 Materials Science	—	X	X	------
5.17 Contamination	X	—	X	------
5.18 Exposure	X	—	—	------
5.20 Fluid Physics	X	—	X	High Speed Film
5.22 Component Test	—	X	X	LWIR Sensor
5.23 Primates	—	X	X	Primates
5.27 Physics & Chemistry Lab	—	X	X	------

SECTION 3

MODULE AND SUBSYSTEMS DESIGN

3.1 CONFIGURATIONS

3.1.1 BASELINE COMMON MODULES. Baseline common modules evolved from the design and analysis of concepts are depicted in Figure 3-1. They consist of three modules: one free-flying and two that operate attached to the space station. The experiment allocations listed in Table 3-1 show that five CM-1s, five CM-3s, and three CM-4s are required.

During the commonality analysis, experiments were assigned to particular modules based on individual subsystem requirements and other indications of common usage of a single module design. These common module designs provide for all experiments defined by the ground-rule program.

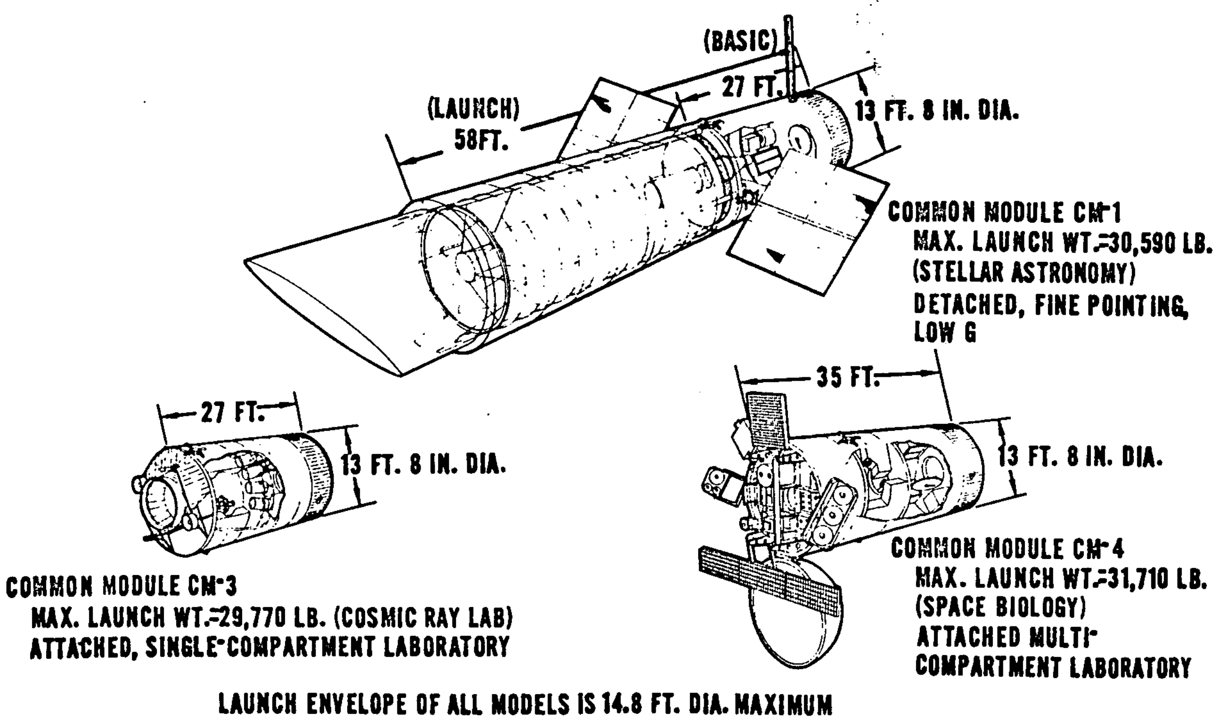


Figure 3-1. Baseline Common Module Set

Table 3-1. Common Module FPE Allocations

FPE	CM-1	CM-3	CM-4	Experiment Peculiar Requirements
5.1 X-Ray	X			
5.2A Stellar	X			
5.3A Solar	X			
5.5 Hi-Energy	X			
5.7/12 Plasma Physics		X		
5.8 Cosmic Ray		X		
5.9/10/23 Biology			X	Sensor Bay Centrifuge
5.11 Earth Survey			X	End Dome
5.13C Centrifuge				Centrifuge
5.16 Materials Science		X		
5.20 Fluid Physics	X	X		Propulsion Slice, 2 Tanks
5.22 Component Test			X	
5.27 Physics/Chem.		X		
Subtotal Modules	5	5	3	
Total Modules		13		
Total Experiment Peculiar		7		
TOTAL		20		

A maximum effort has been expended to gain the economic advantage of subsystem commonality among the free-flyer CM-1 and the attached modules CM-3 and CM-4. See Figure 3-2. The thermal control system uses a two-fluid system (water inside, freon outside) with exchanger at the pressure shell plus a water evaporator backup. A common external radiator panel design is used. The additional length of CM-4 relative to CM-1 and CM-3 affords the additional 250 square feet of radiator area. The free-flyer has solar cell panels, whereas the attached module obtains electrical power from the space station.

The free-flyer requires a wideband data rf transmission link, whereas the attached module uses a hardline connection to the space station. The lesser data transmission

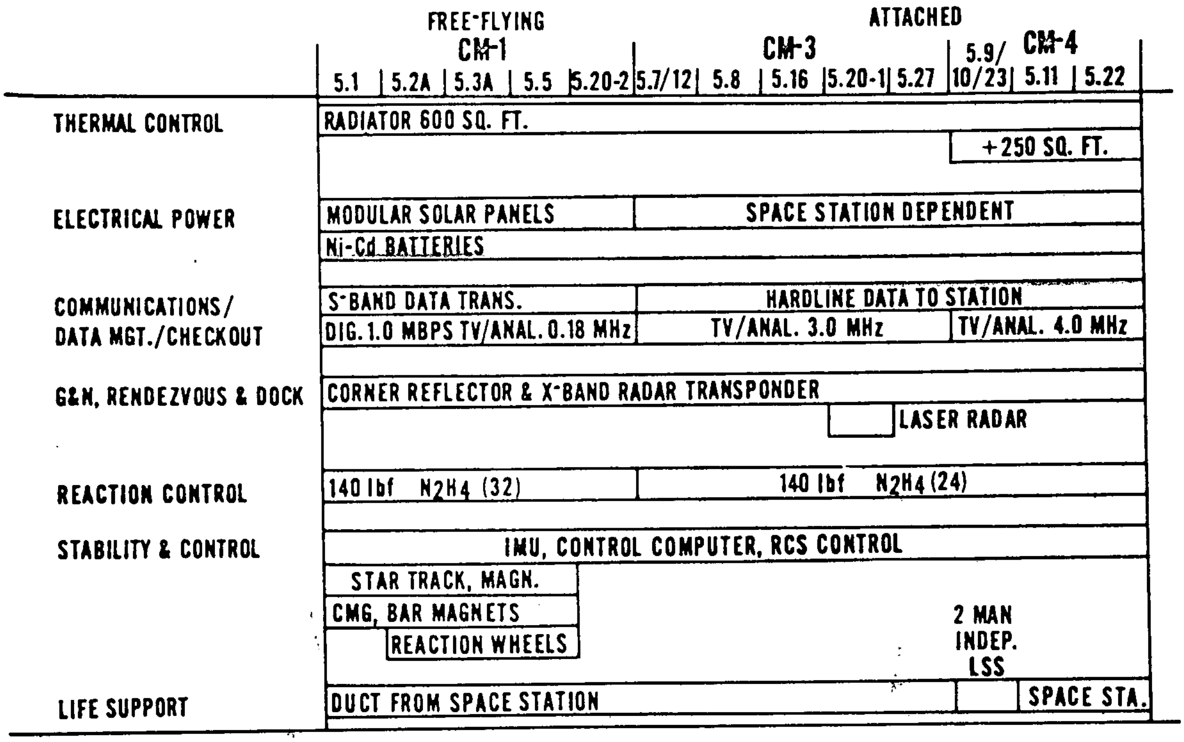


Figure 3-2. Subsystems Commonality

capability for the free-flyer relative to the attached module reflects the desire to minimize radiated power and bandwidth in the interest of economy.

The G&N R&D system is the same for the attached and free-flyer. For attached modules the system is used for initial delivery and subsequent docking port change. A special provision is the addition of a laser radar sensor for the fluid physics (5.20-1) experiment installation in CM-3 to permit the docking of another experiment module.

The reaction control subsystem is identical for all modules except that eight thrusters of the free-flyer 32-thruster system are left off of the attached module. The stability and control subsystem is identical for the free-flyer and attached modules with respect to RCS control. A momentum actuator/dumping system is added to all the astronomy experiment free-flyers. A fine point capability via reaction wheels is added to all astronomy modules except 5.1, where arc-second stability is not currently required. The environment control/life support system is identical for all modules except the space biology FPE 5.9/10/23 where a separate two-man independent system is added to isolate the experiment subject compartment from the space station. For all other experiments the subsystem is simple since it derives support from the space station.

As shown in Figure 3-3, common modules CM-1, CM-3, and CM-4 have identical structures with respect to pressure wall, frame spacing, docking structure, end bulkhead, hatch, RCS mount, and launch vehicle attachment. CM-3 is similar to CM-1 except that a flat pressure bulkhead is added. The bolt-and weld seal attachment of all pressure bulkheads is similar. Common module CM-4, with three pressure bulkheads, can provide three pressurizable compartments.

3.1.1.1 Common Module CM-1. The free-flying CM-1 shown in Figure 3-4 will accommodate any of the five experiment groups listed in Table 3-1. All experiments are mounted on the end pressure bulkhead except the materials science and processing chamber, which is mounted on the side wall frames. Subsystems are mounted adjacent to the docking bulkhead and may be thermally shielded from the experiment components An inboard profile is shown in Figure 3-5. Modularization of some of the subsystems listed in Table 3-2 allows the matching of performance capabilities with experiment requirements.

3.1.1.2 Common Module CM-3. CM-3 is a single-compartment laboratory module that docks and remains attached to the space station, from which it draws electrical power and environment gases. Construction is similar to the other two common modules; subsystem characteristics are listed in Table 3-3.

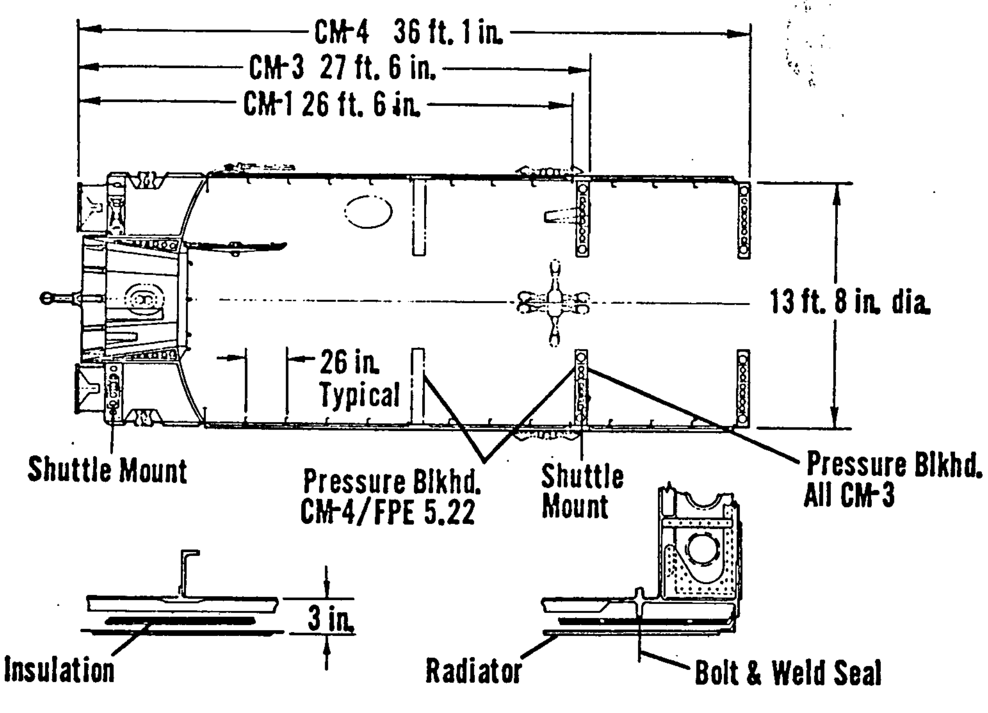
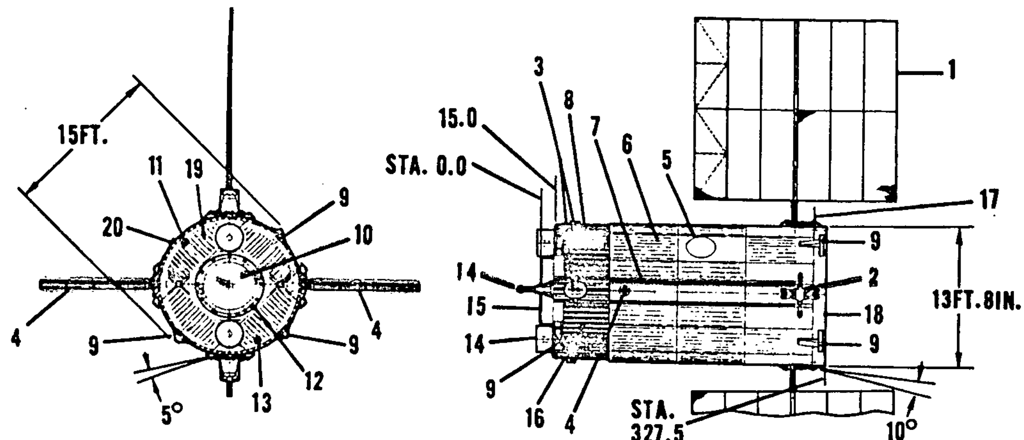


Figure 3-3. Structural Commonality, Common Modules



1 SOLAR CELL ARRAY (660 SQ. FT.)
2 RCS CLUSTER-6 ENGINES (4 PLC.)
3 RCS CLUSTER-2 ENGINES (4 PLC.)
4 BAR MAGNET
5 EMERGENCY HATCH
6 RADIATOR PANELS (600 SQ. FT.)
7 EVA HAND RAILS
8 S-BAND ANTENNA (3)
9 SHUTTLE PICKUP RECEPTACLE
10 ENTRANCE HATCH (5 FT. DIA.)
11 CORNER REFLECTOR
12 TUNNEL SUBSYSTEMS CONNECTIONS
13 COARSE SUN SENSOR
14 DOCKING MECHANISM
15 TUNNEL MATING INTERFACE
16 X-BAND ANTENNA (3)
17 XMOD MATING PLANE
18 EXPERIMENT-PECULIAR BULKHEAD
19 METEOROID PROTECTION
20 STAR TRACKER

Figure 3-4. External Arrangement, Free-Flying Common Module CM-1

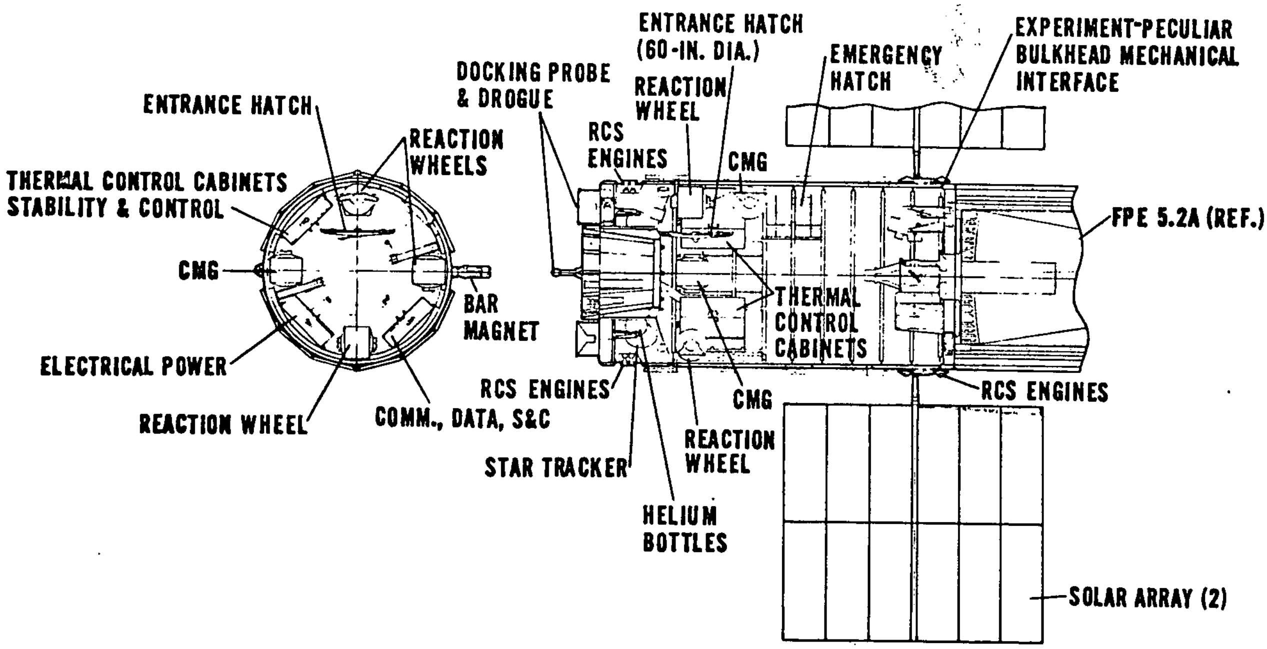


Figure 3-5. Free-Flying Common Module CM-1, Inboard Profile

Table 3-2. CM-1 Subsystems Summary

Subsystem	Description	Typical Parameters
Thermal Control	Active System Water/Freon	9720 Btu/hr 600 sq ft Radiator max
Electrical Power	Solar Panels (2 DOF) 24 × 100W Each Sub-Panel NiCd Batteries (4)	2.4 kW avg 660 sq ft 50 amp-hours each
Communications/ Data Management	Digital Analog/TV S-Band	1 Mbps Capacity 1 MHz Bandwidth 2.2 - 2.3 GHz
G&N Rendezvous/	Laser Reflector (Dock) Transponder (Stationkeeping)	±4 in. accuracy
RCS	Monopropellant Thrusters (Hydrazine)	I_{sp} = 225 sec 32 Thrusters at 140 lbf
Stabilization & Control	Reaction Wheels (3) CMG (2) (2DOF) Magnetic Momentum Dump	900 ft-lb-sec each 300 ft-lb-sec Two 0.5 ft-lb Gimballed Electromagnets

Table 3-3. CM-3 Subsystems Summary

Subsystem	Description	Typical Parameters
Thermal Control	Active System Water/Freon	12,600 Btu/hr max 600 sq ft Radiator max
Electrical Power	Space Station Dependent Interval Batteries, Conditioning & Distribution	3.7 kW avg Capacity 5.3 kW Peak
Comm/Data Management	Hardlines Data to Space Station	3 MHz Bandwidth
G&N, Rendezvous/Dock	Corner Reflector & Transp. Laser Radar	±4 in. Accuracy
RCS	Monopropellant System for Docking	I_{sp} = 225 sec 24 Thrusters at 140 lb
Stabilization & Control	Autopilot for Rendezvous Docking	210 lb, 295 watts

The module is used in conjunction with other modules, each performing discrete functions of a particular FPE. Operationally, this module constitutes the command/ control and data-handling center for the FPE-related detached modules, providing storage, workshop areas, and services. These services include the transfer of fluids, gases, and cryogens onto a docked module.

3.1.1.3 Common Module CM-4. CM-4 is similar in diameter and construction to the other two common modules. It is a multicompartment laboratory module that docks and remains attached to the space station. The three experiment groups have larger volume requirements than those accommodated in CM-3.

A major configuration driver for CM-4 is the Component Test and Sensor Calibration experiment group. This experiment group requires a tunnel airlock in the second compartment.

CM-4 subsystems listed in Table 3-4 are identical to those on CM-3 except that CM-4 requires a separate life support system and the electrical power distribution requirements are higher.

3.1.2 EXPERIMENT INTEGRATION

3.1.2.1 Experiment-Peculiar Integration Hardware. Major experiment-peculiar hardware items required for the experiment program as defined in this study are shown in Figure 3-6. These consist of two centrifuges, a special propulsion unit and tanks for fluid physics experiments.

Since the spin radius experiment requirements for the biomedical and space biology centrifuges require a length of 20 feet, these cannot be mounted to rotate within the 15-foot-diameter common modules. To meet space shuttle payload dimension restrictions, the centrifuge proper is encased in a small-diameter can and the whole is rotated on the external bearing. In orbit, these centrifuges would be attached to the end of common modules. Longitudinal mounting within the shuttle cargo bay would allow simultaneous launch with the related module. Retraction mechanisms could then position the centrifuges for operation.

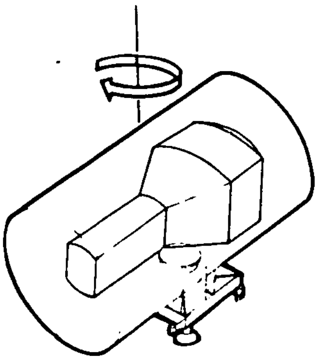
Experiment peculiar hardware required for the fluid physics experiments includes a special propulsion unit (slice) and two cryogenic tank structures. The propulsion slice is permanently attached to the free-flying module pressure bulkhead on the ground during module assembly. After initial on-orbit non-cryogenics fluid physics experiments have been performed, the module would sequentially dock with each of the cryogenics tank units brought into orbit by the logistics system for those experiments.

3.1.2.2 Experiment Integration in Common Modules. Figure 3-7 shows experiment integration by common module and total experiment program hardware required.

Table 3-4. CM-4 Subsystems Summary

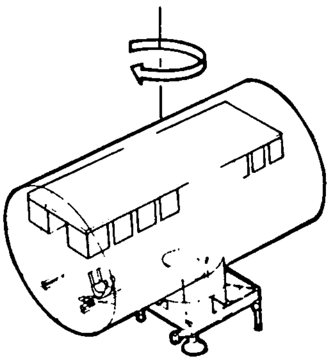
Subsystem	Description	Typical Parameters
Thermal Control	Active System Water/Freon	17,700 Btu/hr max 850 sq ft Radiator max
Electrical Power	Space Station Dependent Integral Batteries, Conditioning & Distribution	5.2 kW avg Capacity 7 kW Peak
Comm./Data Management	Hardlines Data to Space Station	4 MHz Bandwidth
G&N, Rend/Dock	Corner Reflector & Transp.	± 4 in. Accuracy
RCS	Monopropellant System for Docking	I_{sp} = 225 sec 24 Thrusters at 140 lb
Stabilization & Control	Autopilot for Rendezvous/ Docking	210 lb, 295 watts
Life Support	Contaminant Removal CO_2 Removal Atmosphere Replenishment	2 - Man Capacity for Biology Laboratory

BIOMEDICAL CENTRIFUGE CONCEPT



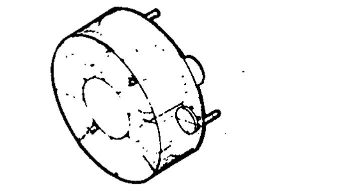
9.5 ft. dia. by 20 ft. long
47 rpm max.
wt. = 6,800 lb.

BIOLOGICAL CENTRIFUGE CONCEPT



9.5 ft. dia. by 20 ft. long
17 rpm max.
wt. = 7,000 lb.

FLUID PHYSICS TANKS (2) & PROPULSION



14 ft. dia. by 6 ft. long
Propulsion Slice wt. = 4,680 lb. dry

14 ft. dia. by 25 ft. long
Max. deployed duration = 113 days
wt. = 9,600 lb. max.

Figure 3-6. Major Experiment-Peculiar Integration Hardware

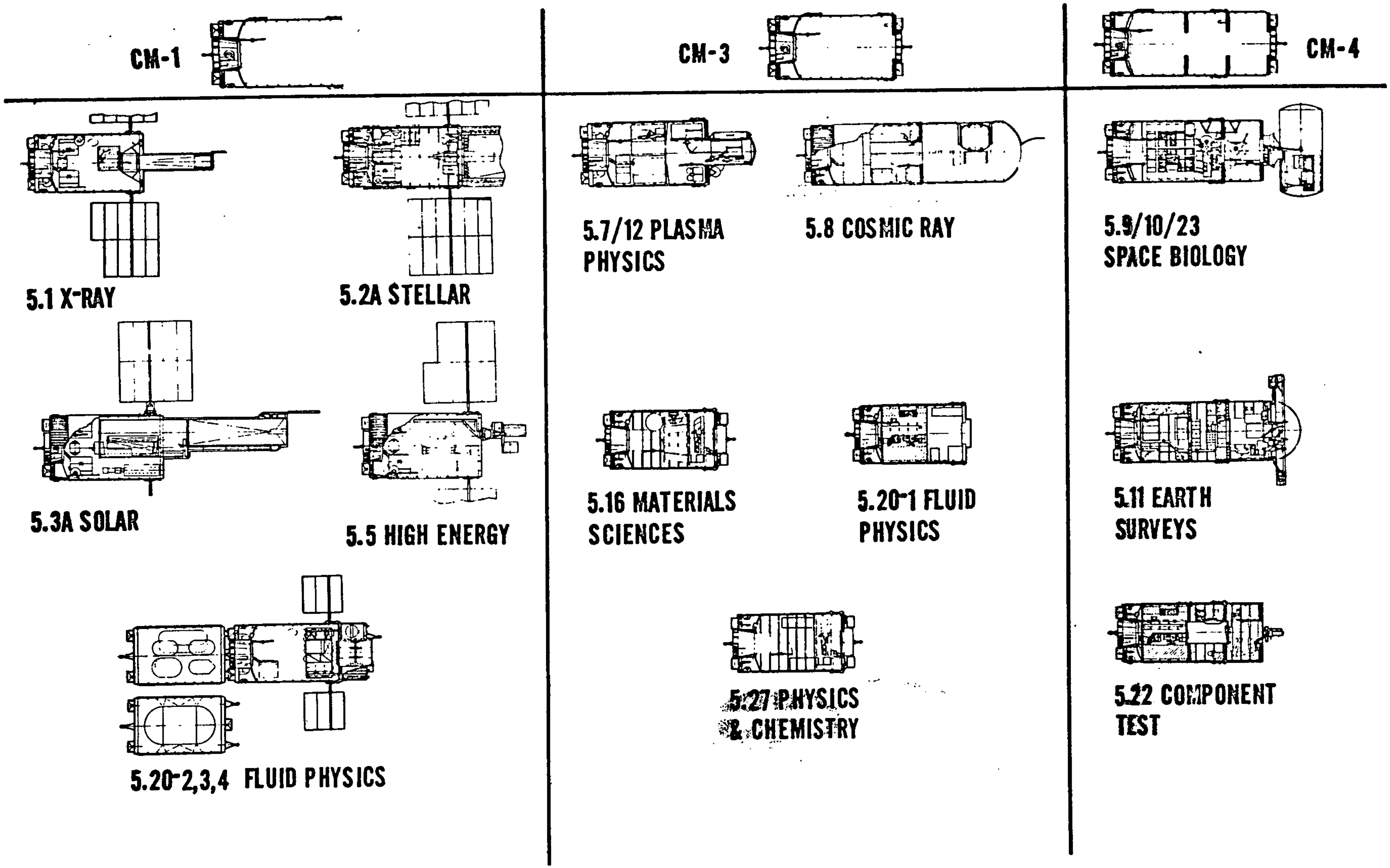


Figure 3-7. Total Program Commonality

3.1.3 ADDITIONAL APPLICATIONS

3.1.3.1 Biomedical/Behavioral/Man-System and Life Support/Protective Systems Experiments Compatibility with the Common Module. Common module design criteria were developed during earlier tasks without including the requirements imposed by Biomedical FPEs, since these experiments are currently assigned as integral experiments in the space station. Compatibility of the modules with the Biomedical FPEs was examined on a preliminary basis, and is presented in detail in Volume III.

3.1.3.2 Detached Earth Surveys Module (FPE 5.11). An investigation was conducted to determine the sensitivity of reassignment of Earth Survey FPE 5.11 to another common module operating in the detached mode. The results of this study are presented in Volume III.

A dual configuration presently under study consists of a detached module (CM-1 derivative) containing the sensors and sensor test area and an attached module (CM-3 derivative) containing the command, data acquisition, and laboratory work area.

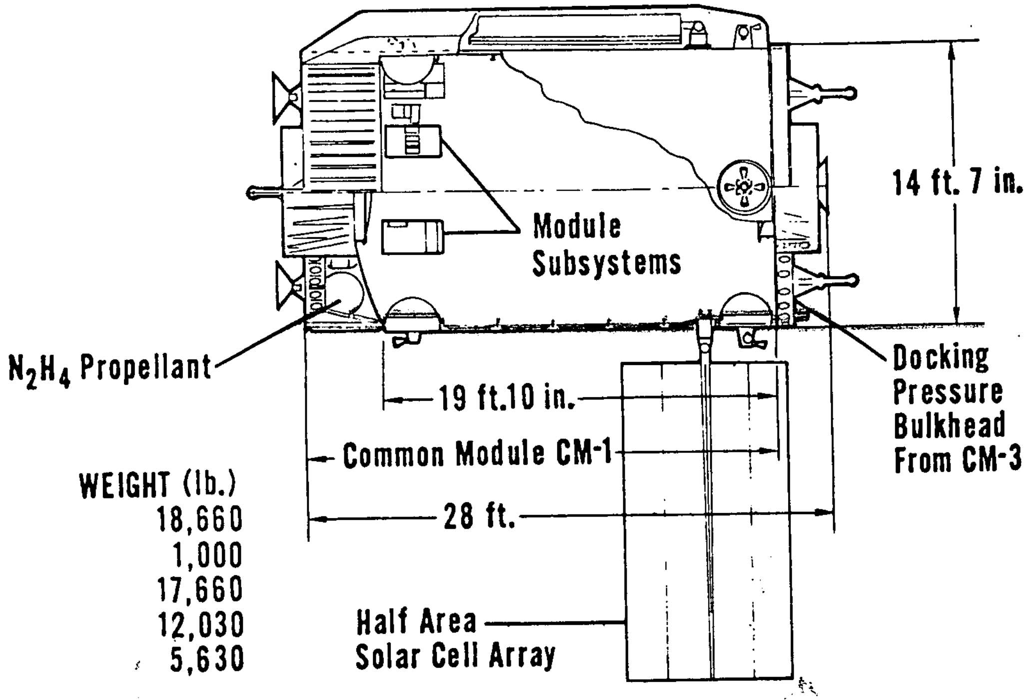
3.1.3.3 Transporter Module. Preliminary concepts of manned and unmanned transporters have been developed. Candidate missions for the unmanned space transporter shown in Figure 3-8 are to transport modules from shuttle to space station, deploy and retrieve free-flying modules, provide orbit maintenance for free-flying modules, relocate modules from one station docking hatch to another, and retrieve disabled free-flying modules.

The manned transporter, Figure 3-9, would have the additional operational capability of remote servicing of free-flying modules. Characteristics are listed in Table 3-5.

3.1.4 MODULE DIAMETER EFFECTS ON EXPERIMENTS. As previously noted, the 13-1/2-foot baseline diameter of the common modules is the largest diameter that can be mounted in the 15-foot-diameter shuttle cargo bay, considering the module external appendages such as solar cell panels, RCS, and bar magnets.

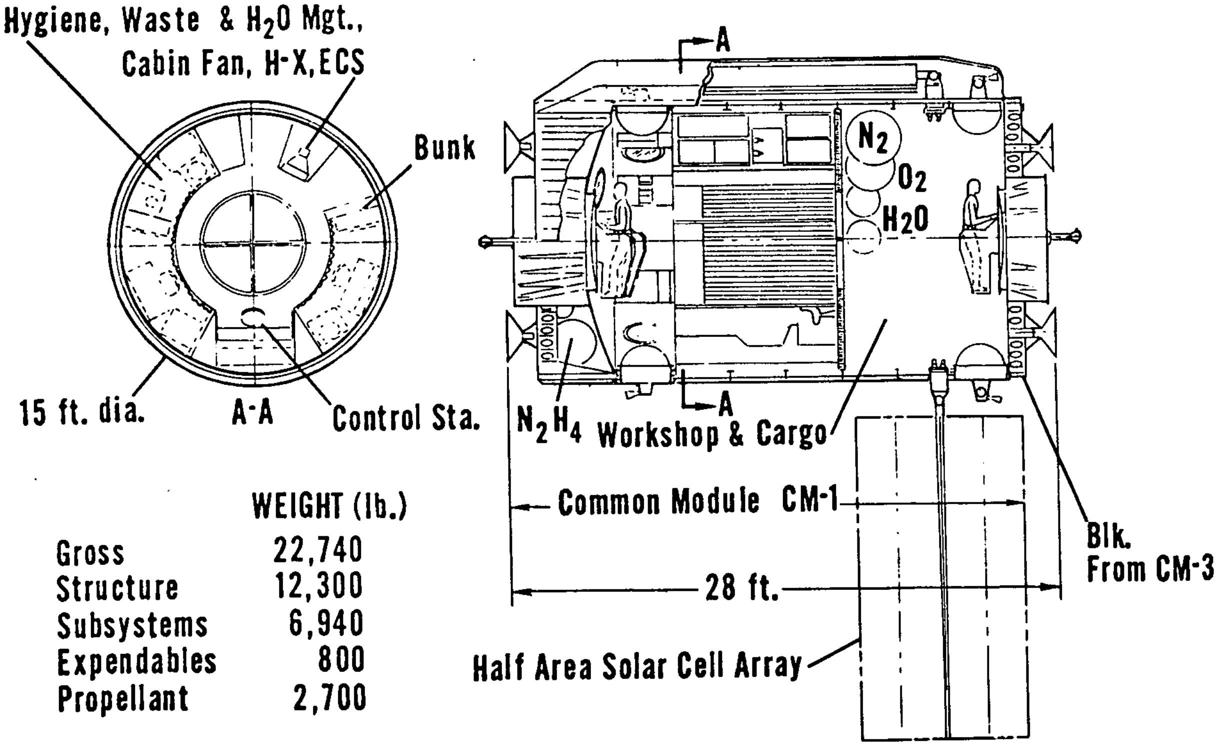
In considering the possibility of a smaller diameter shuttle cargo bay, a study was performed to determine the effects of a reduced diameter on the module and accommodation of experiments.

A summary of reduced module diameter effects on experiments is presented in Figure 3-10. Upper limit sidewall lengths required for CM-1, CM-3, and CM-4 experiments are also shown. The current baseline diameter is considered a minimum for earth surveys and cosmic ray experiments. The baseline diameter CM-1 structure with a 20-foot-long side wall appears properly sized for CM-3 experiment groups. A diameter of 12 feet would eliminate or change these experiments and add one common module for solar astronomy. A further reduction to 10 feet would eliminate or change the RMS and three-meter stellar telescope and add one CM-1 common module for high-energy astronomy. A further reduction in diameter affects all experiment group sizing.



	WEIGHT (lb.)
Max. Gross	18,660
Propellant	1,000
Module Dry	17,660
Structure	12,030
Subsystems	5,630

Figure 3-8. Unmanned Transporter Concept Derived from Common Module CM-1



	WEIGHT (lb.)
Gross	22,740
Structure	12,300
Subsystems	6,940
Expendables	800
Propellant	2,700

Figure 3-9. Manned Transporter Concept

Table 3-5. Transporter Module Characteristics — 5-Day Mission. Crew 2

Performance:	ΔV = 350 fps (FPE 5.2A) to 890 fps Unloaded
Rendezvous & Dock:	CM-1. System Plus Monitor & Manual Override
Structure:	CM-1 Plus Docking Bulkhead & Windows
Power:	CM-1 Less 4 Panels, Each Array
EC/LS:	Heat Rejection: CM-1 Radiator CO_2 Removal: LiOH No O_2 Recovery. No H_2O Recovery Waste Storage & Dump to Space Station O_2 Storage: 295 lb N_2 Storage: 355 lb H_2O Storage: 150 lb

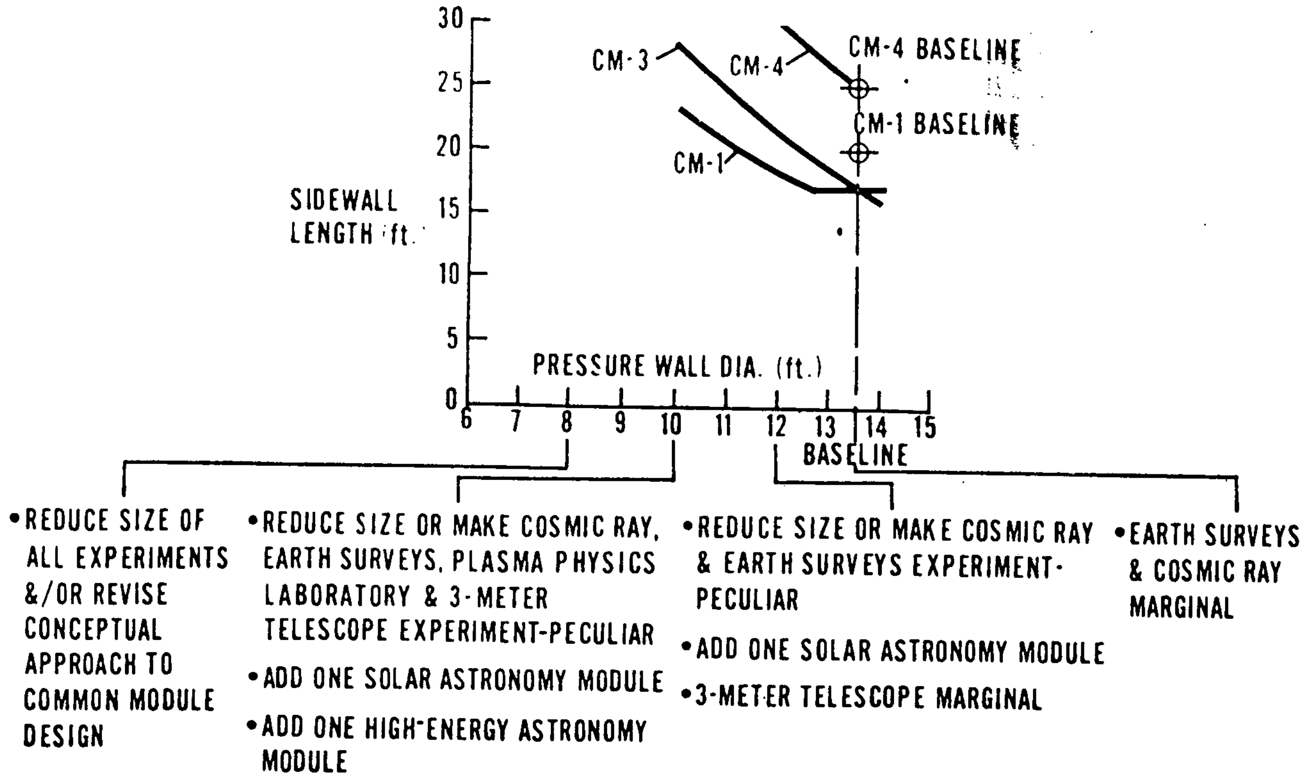


Figure 3-10. Reduced Module Diameter Effects Upon Experiments

3.2 EXPERIMENT MODULE MASS PROPERTIES

Mass properties data has been developed for all experiment module concepts considered in this study, and is summarized in Tables 3-6, 3-7, and 3-8.

3.3 STRUCTURE SUBSYSTEM

To provide realistic predictions of module characteristics, the structural arrangement discussed in the following paragraphs was conceived. Major elements of structure, such as the skirt, dock, hatch, bulkheads and side wall construction, are identical for all three common modules.

A preliminary structural analysis of the shell for meteoroid protection, launch and pressure loads was also performed. The structural arrangement of pressure shell, insulation, and radiator/meteoroid shielding is shown in Figure 3-3.

Table 3-6. Experiment Module Weight Summary — CM-1 Systems Summary and Nominal Dry Weight(1)

Item Condition	FPE 5.1 X-Ray	FPE 5.2A, 3-Meter Stellar	FPE 5.3A Solar	FPE 5.5. High Energy Stellar	FPE 5.20-2, Fluid Physics — Non-Cryogenics	FPE 5.20-3, Fluid Physics — Intermediate Term Cryogenics	FPE 5.20-4, Fluid Physics Long Term Cryogenics
Experiment — Cargo	3,300	8,685	6,875	7,800	5,141	5,776(2)	7.568(2)
Structure	7,749	10,629	9,162	7.911	6,579	9,979	9,979
Propulsion — Dry (3)	—	—	—	—	4,412	4,412	4,412
Reaction Control — Dry	1,161	1,161	1,161	1,161	1.161	1.161	1,161
Electrical Power	1,859	2,084	1,934	1,859	1,519	1,673	1,365
Guidance & Navigation	45	45	45	45	45	45	45
Stabilization & Control	1,061	2,172	1,908	1,468	285	285	285
Communications & Data Management	343	343	381	343	343	343	343
Environmental Control & LSS	177	177	177	177	177	177	177
Thermal Control & Environmental Protection (1)	2,604	2,604	2,604	2,604	2,604	2,604	2,604
Total (1)	18,299	27,900	24,247	23,368	22,266	26,455	27,939

Notes: (1) Includes Radiator Fluid & EC/LSS Expendables
(2) Includes 2,316 Lb. Dry FPE 5.20-2 Experiment Equipment
(3) Propulsion Slice, See Table 2-35
(4) The same CM-1 Basic Module is used for all Detached Mode Fluid Physics Experiments

Table 3-7. Experiment Module Weight Summary — CM-3
Systems Summary and Nominal Dry Weight

Item Condition	FPE 5.7/12, Plasma Physics	FPE 5.8, Cosmic Ray Physics	FPE 5.16, Material Science and Proc.	FPE 5.20-1, Fluid Physics Lab	FPE 5.27, Physics & Chemistry Lab
Experiment - Cargo	5,004	34,180	5,580	785	6,220
Structure	8,411	12,211	7,662	7,662	7,662
Reaction Control - Dry	1,008	1,008	1,008	1,008	1,008
Electrical Power	697	697	697	697	697
Guidance and Navigation	45	45	45	80	45
Stabilization and Control	262	262	262	262	262
Communications and Data Management	451	451	451	451	451
Environmental Control and LSS	271	271	271	271	271
Thermal Control & Environmental Protection	2,032	2,032	2,032	2,032	2,032
Total	18,181	51,157	18,008	13,248	18,648

Table 3-8. Experiment Module Weight Summary — CM-4
Systems Summary and Nominal Dry Weight

Item Condition	FPE 5.9/10/23, Biology	FPE 5.11, Earth Surveys	FPE 5.22, Component Test & Calibration
Experiment - Cargo	12,846	4,602	5,601
Structure	10,848	11,281	13,145
Reaction Control - Dry	1,008	1,008	1,008
Electrical Power	697	697	697
Guidance & Navigation	45	45	45
Stabilization & Control	314	314	314
Communications & Data Management	451	451	451
Environmental Control & LSS	841	415	414
Thermal Control & Environmental Protection	2,747	2,708	2,708
Total	29,797	21,521	24,383

Examination of the cantilevered solar panel array for minimum frequency of vibration indicates a lowest symmetric mode at 1.5 Hz and a lowest antisymmetric mode at 2.3 Hz. Further analysis of astronomy stability requirements will establish panel stiffness requirements.

3.4 STABILIZATION AND CONTROL SUBSYSTEM

3.4.1 REQUIREMENTS. Major considerations in the design of the experiment module stabilization and control subsystem (SCS) are:

a. The astronomy experiment's requirement for fine pointing accuracy to a few arc-minutes (without sighting) and stability to fractional arc-seconds in celestial or sun fixed orientations.

b. Certain space biology, material sciences, and fluid physics requirements for "zero" acceleration environments (10^{-3} to 10^{-5} g maximum).

c. The earth surveys and cosmic ray experiments' requirement for an earth-fixed orientation with module pointing accuracy to 0.5 degree and stability at 0.03 deg/sec.

d. Certain fluid physics experiments' requirement for continuous thrusting at 10^{-3} to 10^{-6} g levels.

e. Execution of commands to perform module delivery from either the space shuttle or an expendable launch vehicle. While some deliveries require final docking only, the more demanding delivery requires orbit circularization at apogee of a 100 × 270 n.mi. parking orbit, followed by space station docking. An infrequent docking port change for normally attached modules is also to be provided.

f. Execution of commands needed to preserve a co-orbiting or stationkeeping situation, and rendezvous and docking (for detached operation).

Maximum utilization of the space station is embodied in an attached operating mode. For this mode, it has been estimated that the space station will provide a pointing accuracy of 0.25 degree and a stability of 0.001 deg/sec. In addition, a "zero" acceleration environment at 10^{-3} g maximum has been estimated for experiments hard mounted to the space station.

3.4.2 SYSTEM DESCRIPTION. Requirements a, e, and f are provided by the SCS configuration shown in Figure 3-11 in the free-flying module CM-1. The numbers within parentheses in each component box are the quantity required to meet functional plus redundancy requirements. Star trackers are used to provide a highly accurate reference to an inertial measuring unit (IMU), which serves as the source of continuous attitude and linear motion data. All guidance is from external sources (space station) and is received in the form of attitude and ΔV programs or discrete commands. In a typical application, the module is maneuvered in attitude with the two control moment gyro (CMG) actuators providing primary torque. Subsequently, the control is shifted

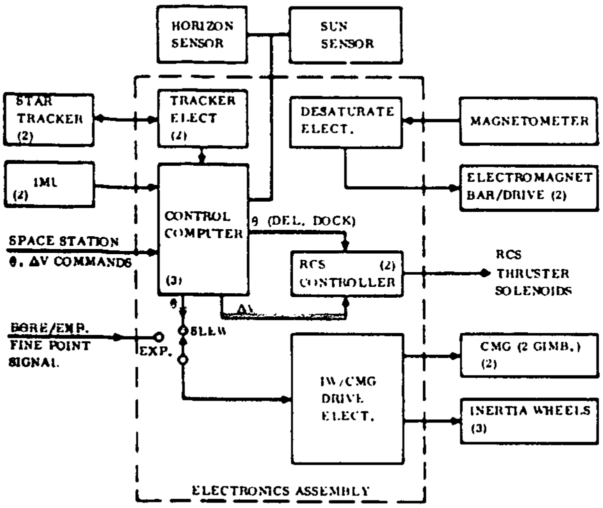


Figure 3-11. CM-1 Stability and Control Subsystem

entirely to three orthogonally oriented inertia wheels (IWs) whose actuation is based on sensor signals derived from the experiment sensor or a separate bore-sighted fine-point sensor. IW momentum dumping is provided by a double-pivoted bar electromagnetic reacting against the earth magnetic field. All ΔV applications for initial delivery, stationkeeping, and dock/undock operation is by command from external source and executed via the module reaction control subsystem (RCS). The horizon and sun sensor units are functionally identical to the star trackers, but because they are less accurate they are not generally sufficient for experiment operation. However, they are an order of magnitude less expensive and are sufficient for module recovery. They are used for that purpose in the event of star tracker failure.

Requirement d is provided by the CM-1 and propulsion slice combination. Attitude control during the experiment is provided by vectoring the two propulsion slice thruster assemblies giving the continuous 10^{-3} to 10^{-6} g acceleration. The CMG, IW, and magnetic dumping elements are not required. Experiment modules CM-3 and CM-4 are physically different attached modules, but contain identical SCS provisions.

Table 3-9 summarizes the overall interface of the SCS system with the common experiment module system.

Table 3-9. SCS Summary Data Tabulation

COMMON MODULE	OPERATING MODE	WEIGHT (lb)	SIZE (ft^3)	POWER (watts)	IW(1) SIZE (ft-lb-sec)	CMG(2) SIZE (ft-lb-sec)
CM-1(6)	Detached	1866/1226(3)	31(4)	927/649(5)	900	300
CM-3, 4	Attached	210	2.11	295	—	—

(1) Three units required; capacity is per unit.
(2) Two units required, capacity is per unit.
(3) The range is due to the variation in dumping bar magnet weight (160 to 800 lb).
(4) Does not include bar magnet. About 21 ft^3 is due to IW and CMG.
(5) The range is largely due to the inertia wheel power drain dependency on CM-1 moment of inertia.
(6) The data applies to the astronomy installations but not to the fluid physics (FPE 5.20-2) free-flyer. 5.20-2 is about the same as CM-3, 4.

3.4.3 DESIGN RATIONALE. In the tradeoff between an all-CMG pointing actuation system with the selected combined CMG/inertia wheel system for the free-flying modules, the combined system was selected because pointing with CMGs could cause an unacceptably large actuation error for astronomy fine-pointing experiments, thereby forcing the provision of a vernier system within the experiment. The vernier approach appears feasible but would necessarily be part of the experiment and probably different for each. The current approach to fine pointing allows a common design approach with maximum experiment support.

The use of IWs for fine pointing does introduce penalties. Electrical power demand for IWs is well in excess of that for CMGs, and IWs inherently do not offer the torque capability needed for module maneuvering (currently set at 6 deg/min maximum).

The maneuvering could be provided by RCS, with a fuel penalty, or by adding CMGs. The CMG approach was taken because its added weight was exceeded by the otherwise needed RCS propellant within a few months.

Regardless of whether an all-CMG or combined CMG/IW system is used, momentum dumping is needed and could best be supplied by either a millipound ammonia-fueled resistojet thruster or the selected magnetic dumping system. The magnetic dumping system has a high initial weight but within about six months, this weight is exceeded by the otherwise needed propellant.

3.5 GUIDANCE AND NAVIGATION

The guidance and navigation subsystem consists of the sensory hardware required to characterize the current orbit of experiment modules operating separately from the space station and the software required to calculate orders by which the module orbit or orientation may be altered. Specifically, this subsystem will serve to:

a. Characterize the orbit of and initiate rendezvous maneuvers for all experiment modules delivered to the space station.

b. Generate orders for deployment and rendezvous of modules operating in detached mode.

c. Track modules during the module/space station rendezvous phase so as to generate midcourse correction orders as necessary.

d. Generate stationkeeping and experiment-oriented module attitude commands as required.

e. Provide for automatic docking of the modules (with manual backup) through measuring module angular position, range, and range-rate relative to the space station docking port and generating the necessary orders for docking.

The tracking sensor used during the rendezvous phase must be capable of pointing in any direction in a hemisphere above the space station. A separate sensor used for docking is boresighted with the docking port and capable of tracking down to zero range. Major hardware is located on the space station. Orders for module maneuver will be generated on the space station and transmitted to the remotely operating modules via the tracking, telemetry, and control (TTC) link, which is a part of the communications and data management subsystem. Equipment carried aboard the experiment module will be restricted to that needed to augment the tracking signal.

The recommended configuration is shown in Figure 3-12. The rendezvous radar is an X-band, interrupted continuous-wave radar. This radar will be capable of skin tracking the module to a range of approximately 50 n. mi. An X-band transponder feeding an omni-directional array placed aboard the module increases the tracking range capability to 500 n. mi. Initiation of the rendezvous maneuver is based on a priori knowledge of the module orbit from TTC data, or data from the rendezvous radar. Midcourse corrections are made using the rendezvous radar to range- and angle-track the module.

The docking subsystem, also shown in Figure 3-12, uses a laser radar of the type under development by ITT Federal. This radar is boresighted to the docking port and tracks a corner cube reflector on the module. Docking is fully automatic, with

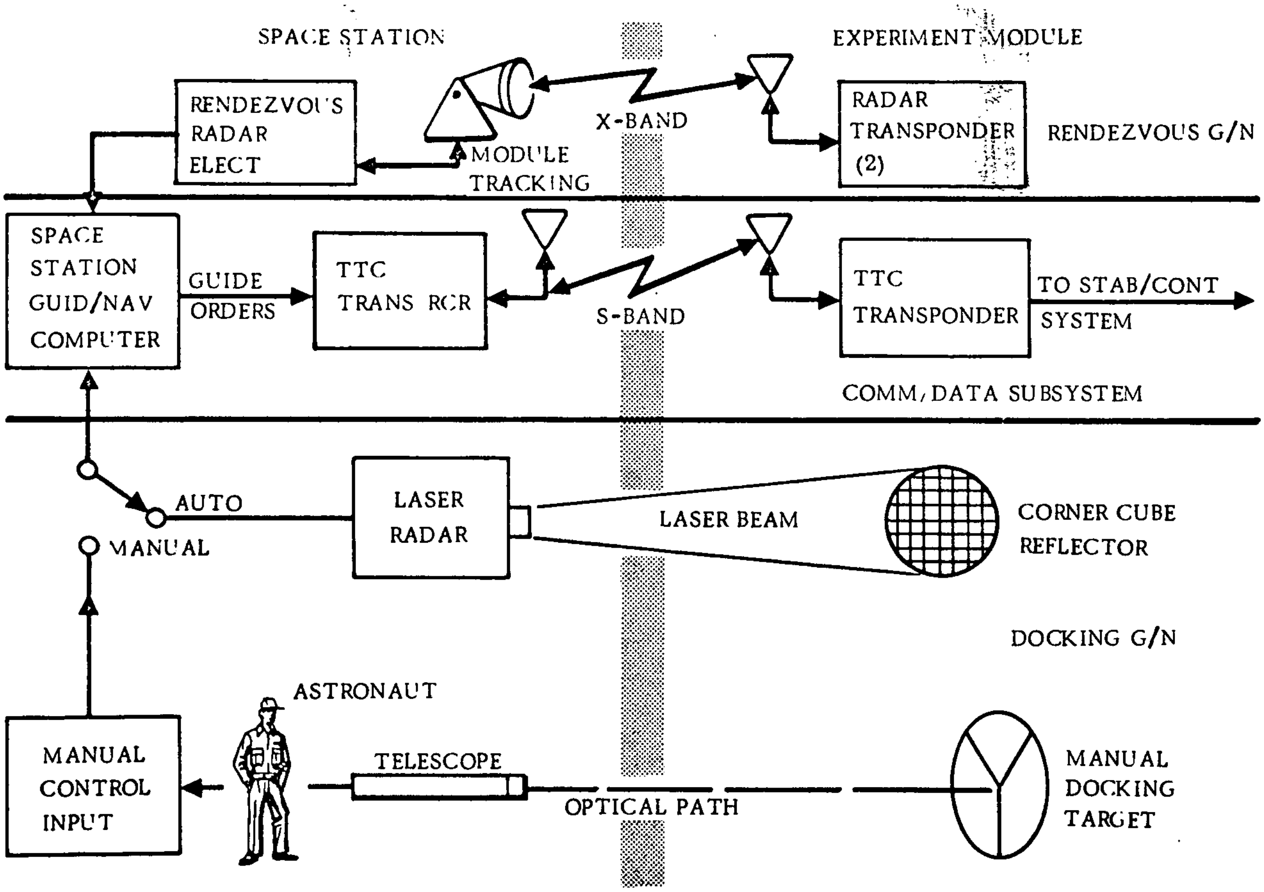


Figure 3-12. Guidance/Navigation Subsystem

provision for operator monitoring and manual intervention. A fully manual backup docking system, similar to that used with the Apollo, will be provided also. As for the rendezvous system, docking maneuver orders are calculated on board the space station and transmitted to the module over the TTC link.

The rendezvous radar identified in the baseline system has been selected over the current LEM radar and other possible radar because it may be designed and built as a fully solid-state system, leading to lower weight and power with higher reliability.

3.6 PROPULSION/REACTION CONTROL SUBSYSTEM

3.6.1 REQUIREMENTS. The free-flying (CM-1) and attached (CM-3 and CM-4) modules require a reaction control subsystem (RCS) for orbital circularization after release from an expendable delivery vehicle, followed by rendezvous and docking. The attached modules can also be moved from one docking port to another location on the space station by using the RCS system. Stationkeeping for the free-flying module is provided by the RCS.

Low artificial gravity forces for the fluid physics experiments are provided by the propulsion slice/CM-1 combination. The propulsion slice houses two gimballed thruster assemblies, which provide thrust levels at 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6} g.

3.6.2 SYSTEM DESCRIPTION. A diagram of the selected RCS concept is shown in Figure 3-13. It consists of a helium-pressurized hydrazine monopropellant feed system supplying fuel to multiple thruster assemblies. Roll, pitch, and yaw rotation and vertical, lateral, and longitudinal translation can be provided by this reaction control arrangement.

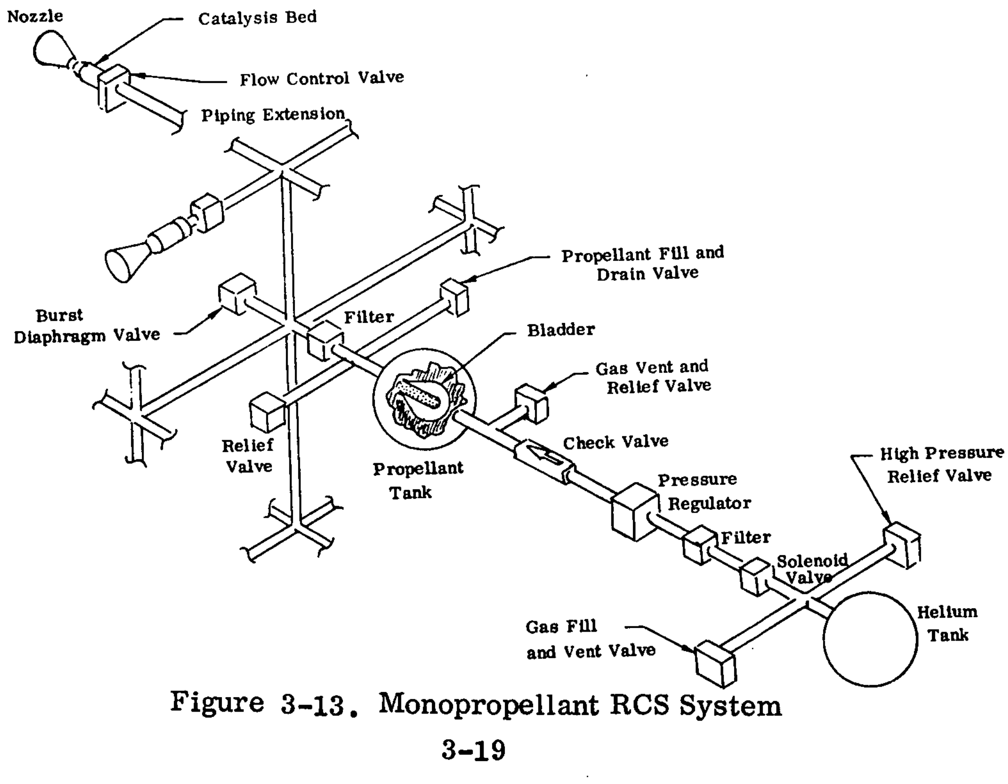


Figure 3-13. Monopropellant RCS System

The complete RCS is summarized in Table 3-10.

Table 3-10. Hydrazine Monopropellant RCS Characteristics

Characteristic	Attached Module	Detached Module
No. of Thrusters	24	32
Thrust Level (lb)	140	140
Hydrazine Propellant Weight (lb)	2560	2560
Propellant Tank System (lb)/no.	150/4	150/4
Pressurization System Dry Weight (lb)/no.	289/4	289/4
Helium Weight (lb)	20	20
Thruster System Weight (lb)	367	490
Total Dry Weight (lb)	806	929
Total Net Weight (lb)	3386	3509

The RCS is critical to module safety and considerable redundancy has been provided. The design consists of four essentially independent parallel lines. Each line contains pressurant, propellant, and thruster assemblies. An interconnect system is provided between the four thruster assemblies so that any propellant feed line can be made to supply any thruster system. Thirty-two thrusters are provided for the free-flying modules, and 24 for the attached module. Figure 3-4 shows their location. This arrangement of the thrusters provides for efficient lateral and vertical displacement capabilities for all the module configurations regardless of position of the center of gravity. The c.g. is significantly affected by the particular experiment installation.

A common tank and feed system is provided for the attached and detached modules. The propellant capacity was sized for orbital circularization after release from the delivery vehicle, one docking and one change of docking port on the space station.

Propulsion system characteristics for the propulsion slice element are presented in Table 3-11. The monopropellant hydrazine approach was used in the higher thrust range, while ammonia resistojets were used at the lowest level. Four levels of thrust are provided. There are two identical gimballed thrusters at each level that can provide vehicular control during the low artificial gravity fluid physics experiments.

3.6.3 DESIGN RATIONALE. The monopropellant hydrazine system approach was selected over the higher performance cryogenic or storable bipropellant system approaches for combinations of the following considerations: 1) hazard potential 2) contamination problems 3) system design, operation, and logistics simplicity.

Table 3-11. Propulsion Slice System Characteristics

	10^{-3} g to 10^{-5} g	10^{-6} g
Thrusters		
I_{sp}	230	350
Number	2+2+2	2
Type	Mono, Hydrazine	Resistojet - NH_3
Thrust (lbf), (ea. of 2 engines firing)	15 at 10^{-3} g	0.015
	1.5 at 10^{-4} g	-
	0.15 at 10^{-5} g	-
Propellant Tanks		
Capacity (lbm)/Pressure (psi)	6800/400	690/350
Number & Type	6	2
Gas Pressure Vessels		None Required
Capacity (lbm)/Pressure (psi) (Total)	46/4000	-
Number & Type	2	-
Weights - Total		
Propellant	6800	690
Gases/Fluids	45	None
Dry System	1000	170
Wet System	7845	860

3.7 COMMUNICATIONS AND DATA MANAGEMENT SUBSYSTEM

3.7.1 REQUIREMENTS. The primary function of each of the planned experiment modules is to provide accurate, timely, and relevant experimental data to space station and/or NASA ground station personnel. To assist in performing this task, the communications and data management system (CDMS) aboard each experiment module must properly:

a. Gather the data from the experiment packages.

b. Perform required accumulation, correlation, transformation, and other data processing.

c. Format the data either for relay to the space station and/or ground stations or for storage with delivery in "hard" form at a later time.

To ensure successful mode operation, the CDMS must also provide for telemetry and command signals between the modules and the space station and/or ground station.

Detached operations entail using the experiment complement aboard a module to collect scientific data. The current concept calls for module orbits that are essentially coplanar with the space station at distances ranging from 10 to 500 n.mi. In this mode, experiment data is normally transmitted by a radio frequency link from the module to the space station.

A major requirement imposed on the subsystem during attached operation is crew safety and monitoring. All modules are manned when they are attached to the space station for experiment operation, routine maintenance, calibration, or replenishment of expendables. Whenever man is aboard, his safety and his ability to communicate verbally and via television are paramount considerations.

3.7.2 SYSTEM DESCRIPTION. The baseline CDMS recommended for meeting the preceding requirements is shown in Figure 3-14, with typical information transfer rates indicated in Table 3-12. These rates were derived specifically for the earth survey module (FPE 5, 11) but are generally applicable for all of the modules with a maximum relay data rate capability of about 1 megabit/second.

The computer, a small aerospace unit, is the primary data processing element. Required flexibility is achieved through software modification from program to program. It interfaces directly with the common data bus and a direct I/O channel to the data formatting and switching (DF&S). The former interface unit is similar to a bus interface unit (BIU) but is designated a computer interface unit (CIU). Several functions are required of the CIU. It must:

a. Provide timing and control of the data bus.

b. Provide data buffering and word formatting capability.

c. Provide detection for the data bus.

d. Handle status and interrupt information from the subsystems to the computer.

e. Multiplex and de-multiplex data.

The computer interface of the CIU will be both with the computer processing unit (CPU) and direct memory access. A dedicated path to the DF&S simplifies the data bus. This may be parallel or serial depending on the rates needed. Both telemetry and low rate data channels use this path. The purpose of the DF&S is to prepare data for transmission external to the module. As all inputs and outputs are digital, the DF&S consists almost entirely of switching circuits. The exception is digital clock generation for clocking data to the transmitters, storage, or data display.

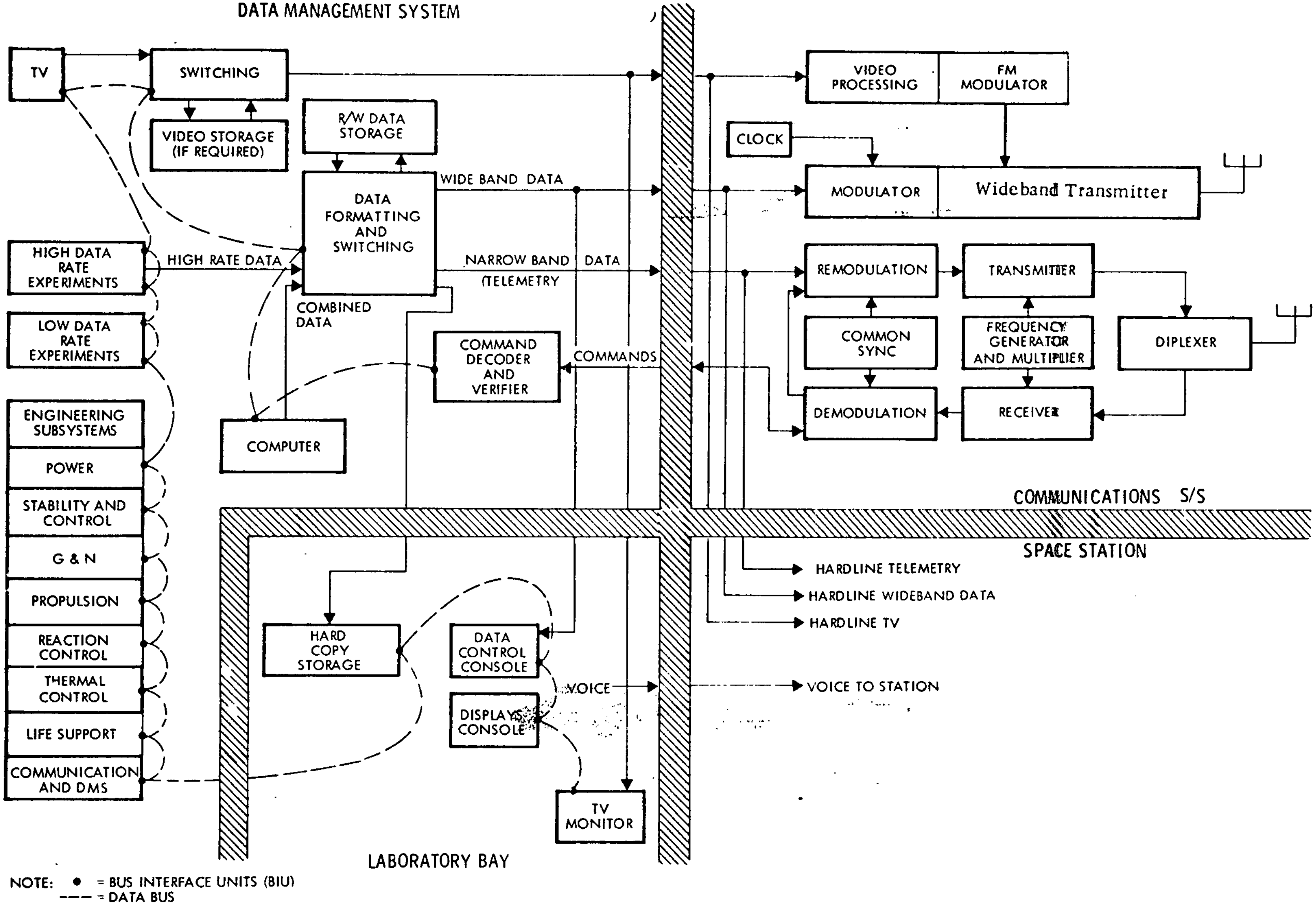


Figure 3-14. Experiment Module CDMS Baseline Concept

Table 3-12. Estimated Information Transfer Rate for FPE 5.11

FROM TO	ENGINEERING SUBSYSTEMS	EXPERIMENTAL SUBSYSTEMS	DATA STORAGE I/O RATE	LABORATORY BAY DISPLAYS AND CONTROL	DATA COMMUNICATIONS
Engineering Subsystems	--	100 bps	5 kbps	5 kbps	5 kbps
Experimental Subsystems	100 bps	--	250 kbps	250 kbps	250 kbps
Data Storage	--	--	--	100 kbps	5 kbps + 250 kbps
Laboratory Bay Displays and Controls	1 kbps	1 kbps	100 bps	--	--
Command Decoder	200 bps	200 bps	100 bps	200 bps	200 bps

The computer uses a fixed CPU with modular memory and it will be a nominally fast machine (4 μ sec add time). A 16-bit word is considered large enough to fit the data requirements of a module. Elaborate calculations are not required, so a fairly simple 20 to 30 instruction set should suffice.

Some key features of the selected baseline approach for the data management equipment are:

a. BIUs are used to interface the experiment sensors to the bus.

b. General housekeeping for the experiment module subsystem and experiments is controlled over the bus.

c. Only low experiment data rates ($\leq$125 kbps) are sent over the bus. High rate data ($\leq$1 Mbps) are sent directly to the DF&S.

d. The computer controls general housekeeping and data management functions along the bus.

e. A single 100-foot-long bus is used, operating at a 200 kHz clock rate to achieve an adequately high information rate.

f. Each BIU can interface with approximately 50 unique input signals; this results in about 15 BIUs for FPE 5.11 (as an example). The BIUs are deployed on a topological and subsystem basis.

In the communications equipment, the RF links are assumed to be in the 1.7 to 2.3 GHz band allocated for NASA services. A 5 watt transmitter output power ensures an adequate signal-to-noise ratio at the space station when the module is at 500 n.mi. This assumes an omni-antenna on the module, a 15-foot dish on the space station and a

station receiving system noise temperature of 1200°K. This wideband transmitter output power allows 1 Mbps digital data narrow band TV/Analog data transfer between the module and the space station at a distance of 500 n.mi., again assuming an omni-antenna on the module. The wideband digital transmitter could be all solid-state.

The tracking, telemetry, and command (TT&C) equipment is the standard universal S-band or space ground link subsystem used with Apollo and compatible with MSFN. The CDMS equipment will weigh a maximum of 229 pounds and consume 363 watts of power.

3.7.3 DESIGN RATIONALE. The many communications networks that can be conceived to satisfy the module communications requirements can be categorized as either line-of-sight (LOS) or as relay links using communications satellites. Of these, the satellite relay mode was not considered the preferrable approach because it would require the use of higher transmitter powers and/or higher antenna gains than the LOS mode. LOS communications was therefore selected.

Of the several frequencies considered for LOS relay (including 140 MHz, 2 GHz, 4 GHz, and 14 GHz), the 2 GHz USB band was selected because of the desire to limit the module prime power required for communications, the decision to use omni-directional antennas (no pointing problems) on the module if at all possible, and the need to transfer wideband information (0.2 MHz TV and 1 Mbps data). Power requirements for various space station antenna sizes and transmission distances were calculated. A range of 500 n.mi. is required in the baseline approach. Some of the tradeoff results are summarized in Table 3-13.

The tradeoff made in selecting a baseline data management approach included methods to interconnect and control the various CDMS components, selection of a suitable computer, and methods of recording and storing onboard data.

A multiplexed data bus was selected rather than conventional point-to-point interconnections to increase operational flexibility and provide for convenient checkout and calibration of the equipment. The bus provides for much better experiment control. A variety of interrelated experiments with aperiodic sampling and special processing requirements can then be accommodated in the different module configurations using common CDMS equipment. A large number of candidate LSI computers (1972 technology) were compared with regard to accuracy, computational speed, and storage and data transfer capability to select and justify the baseline approach. Three data storage and recording methods were considered, including onboard recording on tape or film, transmission to the station for recording and handling, and transmission of video data for real-time viewing. The basic criteria used in determining the selected approach of recording (i.e., most of the data on film and some on magnetic tape) and/or transmitting it to the station were to keep the resulting onboard bulk of recorded materials at a manageable level and to transmit a reasonable amount of data (up to 1 Mbps) to the station for processing.

Table 3-13. Module Transmitter Power vs. Space Station Antenna Size

SPACE STATION ANTENNA SIZE		TRANSMITTER POWER (WATTS) 3 FT	10 FT	15 FT
Module to Space Station Range (n. mi.)	100	5	0.45	0.2
	500	125*	11.3	5.0
	1000	500*	45.0	20.0

*Unrealistic

Fixed Parameters - S-Band, Module Omni-Antenna, 1 Mbps digital data rate, 0.2 MHz Video Bandwidth for TV/Analog.

3.8 ELECTRICAL POWER SUBSYSTEM

The electrical power subsystem (EPS) for the free-flying modules must provide for energy conversion from the prime solar energy source to electrical energy, energy storage for peaking and for dark portions of orbit, and load power conditioning, distribution, and control. The EPS for the attached modules must provide a minimal amount of electrical power during the free-flying mode of rendezvous and docking but its primary function is to provide conditioning, distribution, and control of electrical power supplied from the space station.

Maximum average power demand for the free-flying modules is slightly over two kilowatts (2033 watts) and for the attached modules is five kilowatts. Maximum peak power demand for all modules is seven kilowatts. Power is required in the forms of unregulated dc, regulated dc, and regulated ac (400 Hz). Power requirements for return to the space station of a free-flying module upon completion of an experiment cycle or for maintenance action after a failure are about one-half kilowatt (640 watts).

The free-flying (CM-1) module EPS includes modularly designed solar panels that can be assembled in increments up to a maximum array area of 660 square feet. The panels are retractable for docking to minimize clearance and shadowing problems at the space station. During normal operation the panels are rotated about one axis, allowing experiment pointing anywhere in the celestial sphere simultaneously with full exposure of the solar panels to the sun. Figure 3-15 depicts conservative ratings of the various major blocks in the EPS with emphasis on the efficiencies of the conversion and storage steps.

This solar array design produces 5.08 kW during sunlight, enabling load peaks of $0.88 \times 5.08 = 4.47$ kW to be met from the array during light periods. The capability of the EPS on a total orbit basis considering battery charging and discharging losses and other losses is 2.4 kW at the loads. Initial capability of the array is greater than that indicated to allow for radiation degradation effects on the solar cells during the mission time.

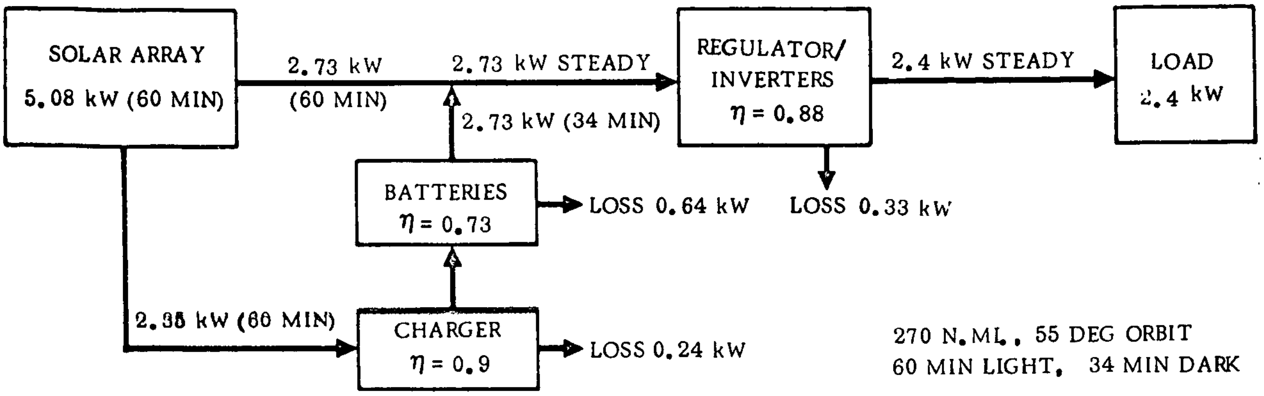


Figure 3-15. Electrical Power Subsystem Block Diagram

Leave-off tailoring of the array configuration will enable the meeting of power requirements for experiments that need less than the maximum design capability of the subsystem.

To achieve the high cycle life requirements of a two year mission before refurbishment, Ni-Cd batteries rated at 50 ampere-hours and operated at 25 percent depth-of-discharge are used as the means of energy storage. Three or more batteries are used. This has the effect of built-in redundancy for module recovery when considering the power requirements for return to the space station. Each battery has an associated battery charger, which ensures optimum charge control from the standpoints of effective utilization of available solar array power and battery cycle life (prevention of overcharge, cell reversal, gassing, etc.).

The attached module (CM-3, CM-4) EPS include batteries to provide power during rendezvous and docking operations. The remainder of the EPS for these modules consists of power distribution (harnessing), conditioning, and control equipment properly sized to handle the power supplied by the space station.

Candidate power source systems considered were batteries only, fuel cells, and solar array/battery systems. Additional brief consideration was given to radioisotope systems. The long mission times eliminate battery and fuel cell systems on a weight basis and cost eliminates the radioisotope systems.

Battery types investigated include Ag-Zn primary and Ag-Zn, Ag-Cd, and Ni-Cd secondary types. Each of these is best applied to one of the various energy storage requirements of the experiment module program, with the Ni-Cd secondary type as the appropriate choice for meeting the basic orbit cyclical demands and the others better (from a weight standpoint) for peak loads with relatively less frequency. The Ag-Zn primary is best for a very high peak load occurring once only. Under these conditions, it can deliver up to seven or eight times the watt-hours per pound of a Ni-Cd. Cost

and design commonality features were also evaluated, and as a result a choice of Ni-Cd batteries for all modules was made. It is intended that the battery design used on the experiment module be the same as that of the space station unless further detailed studies of total life cycle cost factors indicate otherwise.

3.9 THERMAL CONTROL SUBSYSTEM

3.9.1 REQUIREMENTS. The thermal control analysis was directed toward compiling the experiment and subsystem heat loads and examining conceptual means for rejecting that heat from the module. Primary internal heat loads were derived by a compilation of average power consumption and the assumption that this energy would ultimately be rejected as waste heat from using components. The range of heat rejection requirements for the attached CM-1 and the attached CM-3 and CM-4 modules is shown in Table 3-14.

Table 3-14. Common Module Heat Loads

Module	Average Electrical Load (kW_e)	Radiator Area (ft^2)	Heat Rejection (Btu/hr)
CM-1	1.1 to 2.8	600	3,840 to 9,720
CM-3	1.0 to 3.7	600	3,410 to 12,600
CM-4	1.6 to 5.2	850	5,680 to 17,700

3.9.2 SYSTEM DESCRIPTION. The completely active thermal control system shown on Figure 3-18 was selected for both free-flying and attached module concepts. The heat absorption portion of the system uses "cold plate" heat exchangers to absorb the waste heat from experimental packages and other subsystems. The heat transport fluid is water. The heat dissipation portion of the system uses low temperature radiators on the external skin of the module to radiate the waste heat to space. The heat transport fluid in this loop is Freon 21. The two loops are joined together by means of an intercooler heat exchanger at the module pressure wall. The radiators double as the meteoroid protection system and are covered with a thermal control coating to minimize the absorption of solar radiation and maximize the emittance of thermal radiation.

As shown on Figure 3-16, there are two separate cooling systems. Both must be functional during experiment operations. A failure in one system requires shutdown of the experiment. The standby system supplies 24 hours of cooling in the event of a second system failure. The cold plate cabinets housing the critical components have triply redundant cooling loops. Experiment cold plates have a single coolant circuit.

The insulation system chosen for use on the walls of the experiment modules themselves involves the use of layers of high performance radiation shield (superinsulation).

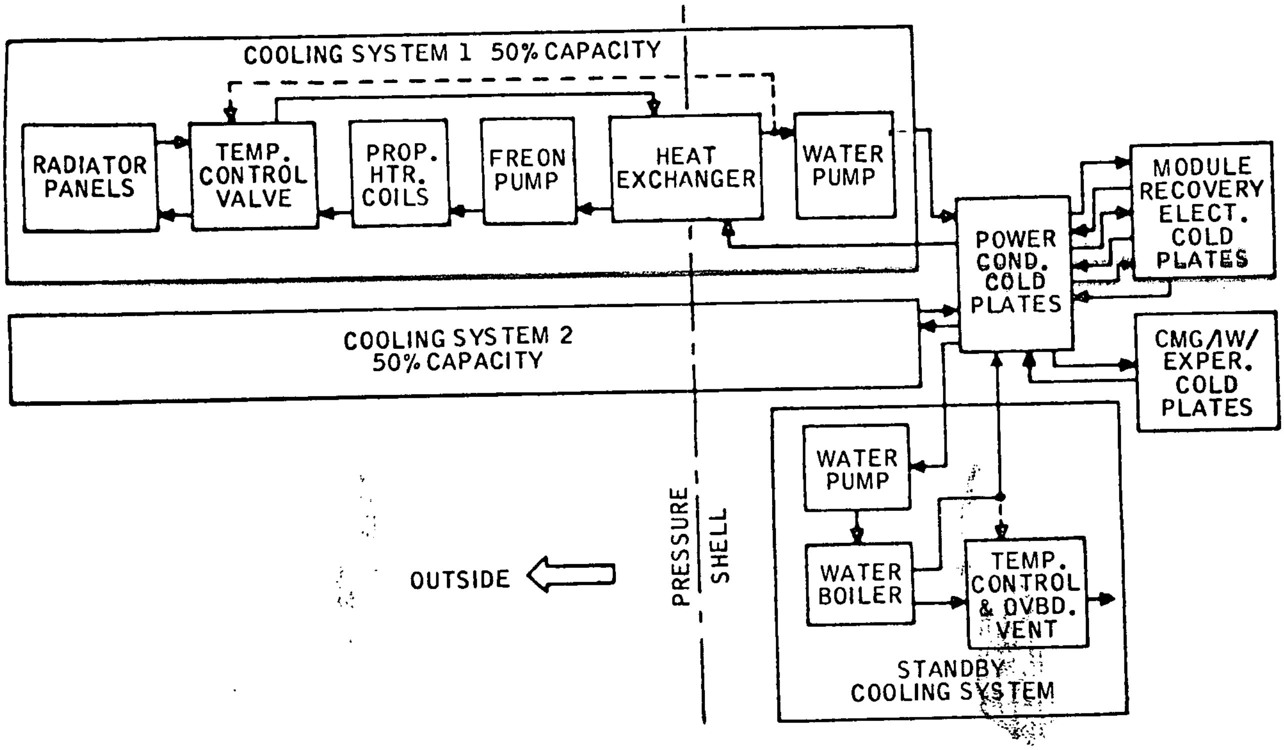


Figure 3-16. Functional Flow Diagram

The total thermal control subsystem weights for the three modules are: CM-1, 1578 pounds; CM-3, 1042 pounds; and CM-4, 1328 pounds. These weights include the cold plate cabinets, wall insulation, and integral radiators as well as the pumps and control systems.

3.9.3 DESIGN RATIONALE. Various concepts were reviewed to develop an approach to thermal control. To establish a basis for these conceptual approaches, the types of components requiring cooling were analyzed and the type of cooling applicable was determined. An analysis was also made on spacecraft external coating requirements and wall insulation. Since some experiment sensors require super-cold and cryogenic temperatures, data was generated on characteristics of closed-cycle refrigeration systems that produce low temperatures. A conceptual approach was established to obtain passive super-cold mirrors for the stellar astronomy experiment to alleviate a temperature tolerance problem and minimize the heat loss through the large telescope aperture.

A survey of subsystem components was made to determine which components required active cooling and which could be passively cooled. To be passively cooled, the components need sufficient area to radiate or conduct heat to passive heat sinks. The location must also be compatible with component accessibility for servicing and maintenance. Those components with operating temperatures that exceed their limit value dissipating

heat by passive techniques require active cooling. Over half of the components surveyed required active cooling. Thus, since a completely passive cooling system was not possible, an active cooling system was selected. A mixed passive-active cooling system was rejected because the dependency of the passive portion on subsystem or experiment arrangement requires a completely new thermal analysis for each configuration. This requirement severely limits the flexibility of module designs.

A study was conducted to determine the capability of an experiment module to reject the heat generated within the module by the use of low temperature space radiators. To perform the study, a worst and best case analysis was conducted to bracket the extent of the experiment module radiator heat rejection capability. Cases were run for maximum earth shadow time, maximum solar exposure time, earth and solar orientations, axial and perpendicular vehicle references and 55° and 28.5° orbital inclinations. The study included the effects of radiant interchange while docked at the space station. Thermal control coating degradation with time was also evaluated. Table 3-15 summarizes the results of the study.

Table 3-15. Typical Values of Integral Radiator Performance

Integrated Average Heat Transfer Rates	21 to 72 Btu/hr-ft^2
Space Station Interference Heat Transfer Rates	0 to 15 Btu/hr-ft^2
Delta Due to Radiator Coating Degradation	-30 Btu/hr-ft^2

As implied by the results shown in Table 3-15, there are situations when the modules will be unable to reject all internally generated heat while docked to the space station. These conditions can be prevented by developing stable, non-degrading thermal control coatings and properly scheduling experiment modules to space station docking ports.

The critical experiment for CM-1 from a thermal control standpoint is FPE 5.2A for Stellar Astronomy. A study completed by Perkin-Elmer concluded that in order to obtain the performance from the three-meter mirror, the mirror and its secondary mirror supports have to be operated at -112°F (-80°C). Passive thermal control techniques appear feasible to obtain the super-cold mirror but produce serious design problems within the module. An alternate approach to the telescope design was developed by Itek Corporation. In this case, the optical system is designed to operate at a nominal temperature of 70°F. The use of a "hot" telescope provides a completely different set of experiment peculiar thermal control problems than the "cold" telescope design. With the Itek concept, it is probable that a considerable amount of thermal energy may be necessary to keep the telescope at a uniform 70°F and make up for the energy loss by radiation to space.

3.10 ENVIRONMENTAL CONTROL/LIFE SUPPORT (EC/LS) SUBSYSTEM

The experiments assigned to CM-1 are performed in a free-flying mode in which the module is always depressurized and unmanned. Hence, EC/LS functions are required

only during crew servicing while attached to the space station. During this time, free atmospheric interchange between the space station and module is allowed. The requirement is to support two men, and consists primarily of pressurization and ventilation functions.

Like CM-1, the attached CM-3 has an EC/LS requirement for a two-man crew with air interchange permitted. Unlike CM-1, however, the requirement is continuous rather than occasional, and the system contains slightly more hardware in order to provide ventilation and pressurization of a CM-1 docked to the outboard end of the CM-3.

The nominal EC/LS equipment within the attached CM-4 is similiar to that of both CM-1 and CM-3. However, for the biology FPEs, additional equipment is provided to isolate the space station atmosphere from that of the biology experiment. To obtain this isolation, the specimens are located in a normally closed-off module outboard chamber. An independent atmospheric control loop is provided for a two-man experiment crew in the in-between or module inboard chamber. This crew area is normally closed off from both the space station and specimen chamber.

Besides the basic requirements imposed by the crew in attendance of the experiment, the major factor dominating the EC/LS design is the support available from the space station. Table 3-16 lists the specific requirements and the selected source of support for the two-man crew in CM-1, CM-3, and CM-4, along with the resultant EC/LS weight and power for each CM.

Table 3-16. EC/LS Subsystem Summary (2-Man Crew)

	CM-1	CM-3	CM-4	
			Nominal	Biolaboratory
Requirements				
Air Flow Control	EM/SS	EM/SS	EM/SS	EM
Air Temperature Control	EM	EM	EM	EM
Air Purification	SS	SS	SS	EM
Pressurization Control	SS	SS	SS	EM
O_2/N_2 Supply	SS	SS	SS	SS
Pressure Suit Circuit	EM/SS	EM/SS	EM/SS	EM/SS
Water Storage & Dispensing	SS	SS	SS	EM
Water Purification	SS	SS	SS	SS
Metabolic Waste Collection	SS	SS	SS	EM
Nutrition & Waste Processing	SS	SS	SS	SS
Subsystem Summary				
Weight (lb)	146	223	386	728
Power (watts)	200	200	300	430

SS = Supplied by space station

EM = Supplied by experiment module

In CM-1, CM-3, and the nominal CM-4, equipment is provided for distribution of conditioned air from the space station, module ventilation, and temperature control, atmospheric pressurization control, and pressure suit use. The pressure suit circuits are required for certain experiments as well as emergencies that require servicing while the module is depressurized. To implement the depressurization/repressurization required by CM-1 during the deployment/servicing cycle, two methods were evaluated. The first assumed repressurization from the space station makeup gas supply system and subsequent venting of this gas to space. The second was to pump the module air into the space station and thus conserve most of it for reuse. The major penalties to be compared here are the make-up O_2/N_2 that must be resupplied and the power required for pump-down. Assuming that the module air could be pumped directly into the space station at approximately 14.7 psia without the resulting pressure rise upsetting the station subsystems, the pump-down power was low enough (about 6 kW-hr) that this technique was selected for use. The assumption involving the space station, however, should be investigated further.

The CM-4 biolaboratory system contains a molecular sieve for carbon dioxide removal, charcoal filters and a catalytic oxidizer for trace contaminant removal, a condenser/separator for relative humidity control, and equipment for occasional metabolic waste collection.

3.11 RELIABILITY/MAINTAINABILITY AND SAFETY ANALYSIS

The objective of this analysis was to develop design guidelines for experiment modules which will minimize the cost of sustaining experiment operations. The cost of providing the high degree of module reliability needed for long life was traded off with the alternative cost of achieving long life through repair. The goal was to define the level of experiment and supporting subsystem reliability with the associated repair that results in the lowest program cost consistent with experiment missions and crew limitations. This lowest cost combination of subsystem reliability and maintenance was determined in accordance with the following key factors as shown in Figure 3-17.

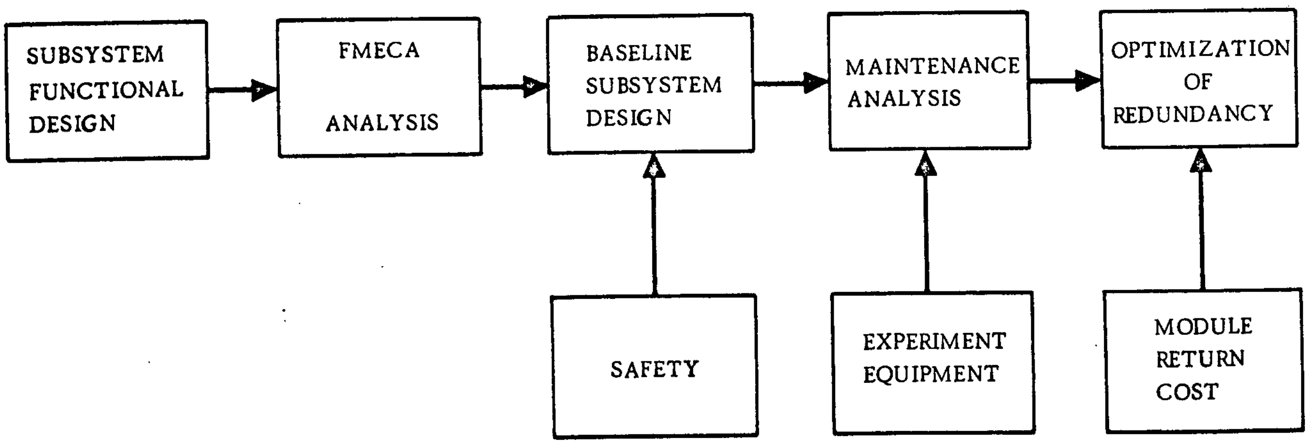


Figure 3-17. Module Reliability/Maintainability/Safety Approach

3.11.1 RELIABILITY. The failure mode effects and criticality analysis (FMECA) conducted on each subsystem used the space station ground rules as the governing criteria in providing backup capability for critical functions. Critical functions for the experiment modules were established as being those connected with safe flight and control of free-flying modules. Functions connected only with continued conduct of experiments were classified as noncritical.

The increase in subsystem cost and weight to provide this safe-flight capability as compared to a purely functional system for the five free-flying modules is shown below.

Net effect on module subsystems weight	393 lb	6.7%
Subsystems volume	9.69 ft^3	3.4%
Subsystem unit cost	\$3.03 M	20.6%
CM-1 module total cost (five modules)	\$15.15 M	20.6%

The majority of the increase was in RCS, stability and control, EC/LS, G&N, and communication and data management subsystems.

3.11.2 MAINTAINABILITY. Module subsystems designed to meet safety requirements have very high reliability for the controlled flight portion of their total operation. With this high reliability of module recovery for repair at the station, the only significant parameter is the expected number of failures — failures that result in the need to return the module to the station for repairs.

These repair trips can be reduced by further increasing redundancy in the subsystems. The cost of increasing redundancy can be compared to the cost of the alternate option: returning to the station for repair. Addition of these two costs, subsystem redundancy, and module return costs will indicate the optimum increase in subsystem redundancy as shown in Table 3-17.

Table 3-17. Optimization of Subsystem Redundancy

Item	Baseline Subsystem	Optimized Subsystem
Failures per Year	3.0	1.2
Cost of Return Trips	\$3.5M	\$1.2M
Subsystem Cost	\$14.7M	\$15.4M
Total Cost	\$18.2M	\$16.6M
Subsystem Weight	5910 lb	6106 lb
Subsystem Volume	289 cu. ft	293 cu. ft

Analysis of increase in redundancy is accomplished using a computer program that adds specific components on the basis of greater Δ R/Δ \$ ratio.

Module subsystem cost is then plotted as a function of the added cost of redundancy to achieve a decrease in the number of failures per year.

The total of these two costs shows a least-total-cost point and related expected failures per year. The indicated increase in subsystems cost will provide a ten-year savings as shown in module return cost.

Three basic free-flying astronomy module concepts were analyzed from the standpoint of crew costs for maintenance and servicing:

Concept A — Partially pressurized subsystems and equipment sensors are housed for IVA access, with the telescope accessible only by EVA.

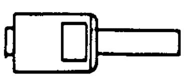
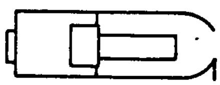
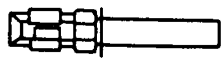
Concept B — Totally pressurized. All major equipment is accessibly by IVA.

Concept C — Totally non-pressurized. All equipment is mounted on a dockable framework for all EVA access.

Crew costs for access to equipment for subsystem and experiment servicing were found to be relatively equal for all three concepts using IVA of one man at 5 hours per operation, and EVA of two men at 3.6 hours per operation.

A major cost increase appeared in Concept B over Concept A baseline due to cost of additional structure and subsystem sizing. Concept C results in a higher program cost due to reduced commonality with attached modules, which impacts Concept C production and RDT&E costs as shown in Table 3-18.

Table 3-18. Comparison of Module Concepts for Maintenance

Concepts	A	B	C
			
Total Crew Cost	3790 hr \$3.79M	\$3.77M	4880 hr \$4.88M
Module Program Δ Costs Above Baseline (\$M)			
DDT&E Production Interface Hardware	Baseline	+61.9 -25.5 -23.9	+90.1 +12.0 -10.3
Total Δ Cost Over Baseline		+63.5	+91.8

3.11.3 SAFETY. The following primary safety guidelines were established during the course of study:

a. A means will be provided to jettison modules from the space station as an emergency measure in the event of a major hazard.

b. Servicing and maintenance of the modules and their experiments will be accomplished without EVA and in a shirtsleeve environment to the maximum possible extent.

c. Appropriate safety features will be incorporated into the design and maintenance features of each module concept.

The concern and detailed design consideration given to the docking phase of the module operation should be noted. As conceived, docking will primarily be automatic. Recognizing the criticality of failure of the required subsystems in close proximity to the station, they have been given enough redundancy to reduce the probability of failure to a low level.

3.11.4 ANALYSIS CONCLUSIONS. The conclusions reached as a result of analyzing module subsystems are:

a. The current subsystem designs, weight, and cost are considered realistic since they reflect considerations of safety and maintenance cost effectiveness.

b. Scheduled return of modules to perform maintenance other than required periodic servicing is not a cost effective operation.

c. Crew cost does not appear to be a significant factor in determination of pressurizable access requirements.

SECTION 4

RESOURCE REQUIREMENTS

4.1 PROGRAM COST ESTIMATE

The program cost estimates resulting from the resource requirements analysis are summarized in Table 4-1 for the experiment module program (consisting of common modules CM-1, CM-3, and CM-4. These costs were determined by a refined version of the parametric cost model and the methodology used during the initial commonality analysis (Figure 4-1). The costs shown are within a confidence of ± 20% in the context of a Phase A study.

Table 4-1. Experiment Module Program Cost Summary Integrated Program (Millions of Dollars)

	CM-1	CM-3	CM-4	TOTAL
Module DDT&E	264.55	151.60	192.50	608.65
(Module Unit)	(20.91)	(15.05)	(16.61)	
Module Production	104.55	75.24	49.84	229.63
Experiments	424.60	121.00	260.20	805.80
Experiment Integration	112.05	39.45	89.32	240.82
Interface Hardware	127.28	13.26	27.54	168.68
Launch Operations	29.53	25.00	16.82	71.35
Flight Operations	120.59	26.08	24.86	171.53
Project Management & Support	11.83	4.52	6.61	22.96
Total	1194.98	456.15	667.69	2318.82

The total program costs consist of 1) design, development, test, and evaluation (DDT&E) or nonrecurring cost, 2) production cost for the flight articles (recurring production), and 3) operations cost (recurring operations). A project management and support function is also included for overall support and management of the three modules, the experiments, and the launch and flight operations. The costs are in 1970 dollars and fee is included.

4.1.1 MODULE DDT&E, UNIT, AND PRODUCTION COST. The modules are assumed to be man-rated space flight hardware of minimum complexity commensurate with performance and reliability requirements. Maximum use is made of developed and qualified off-the-shelf components and assemblies that will be available in the experiment module time span. It is assumed that common modules are developed in an integrated concurrent program that will meet the launch requirements shown in Figure 4-6. Development costs are determined at the subsystem level with subsystem cost estimating relationships (CERs). Unit costs were determined with CERs or point estimates at the system or component level. Sustaining engineering is contained in these CERs and is not estimated separately.

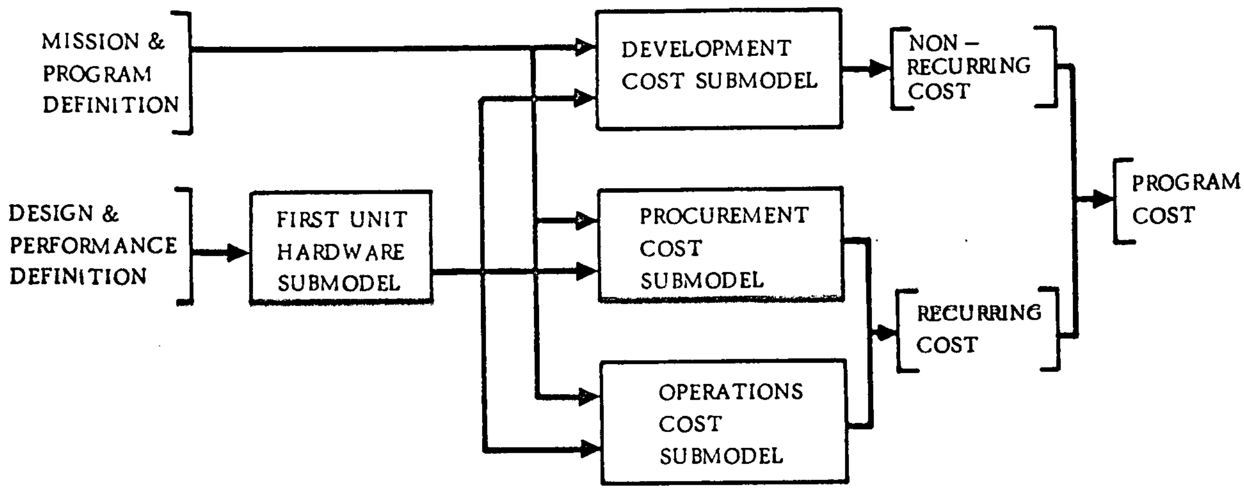


Figure 4-1. Experiment Module Parametric Cost Model

No cost improvement due to learning was included because of the small production quantity and because each module is somewhat different because of subsystem component modularity. This modularity allows the subsystem capability to be more nearly tailored to the experiment FPE requirements.

4.1.2 EXPERIMENTS, INTEGRATION, AND INTERFACE HARDWARE. Experiment hardware costs are based on data supplied by the NASA and are assumed to include experiment DDT&E, prototype and test hardware, flight hardware, initial and consumption spares, and fee.

Experiment interface hardware is defined as those additional items of equipment or hardware necessary for the experiment (as defined in the "Blue Book") to operate when installed in the appropriate common module. Examples of this hardware include experiment mechanical mounting provisions and mounting bulkheads, telescope thermal meteoroid shroud experiment sequencers, experiment deployment arms, and fluid servicing equipment.

The experiment integration considered here is the software associated with the experiment/module interface control (mechanical, thermal, dynamics, electronic, operational, sequencing, etc.) and with control of interactions between experiments.

4.1.3 OPERATIONAL COST. The operations costs in this estimate include launch operations and flight logistics. The experiment modules are assumed to be operated in conjunction with the space station, which will supply all mission operations and control plus data-acquisition functions. No cost was included for independent ground tracking, data acquisition, or mission control. These operational costs are based on five years of mission life for the astronomy modules and two years for all others. Module refurbishment and experiment replacement costs at the end of these experiment mission lives were excluded.

The launch vehicle considered for both the experiment modules and the operation logistic supplies is a space shuttle with a payload capability of 25,000 pounds in 270 n.mi. earth orbit. A baseline launch operations cost of $4.0M for the nominal shuttle was assumed in this study. All experiment modules were charged for the full launch cost and were not prorated by weight even though they may not have used the full weight and/or volume capability of the vehicle. Launch operation costs for logistic supplies were, however, prorated by weight.

Cost estimates for operation experiment data reduction and analysis were excluded as being beyond the scope of the present sutdy.

The operational logistic requirements of these experiment module programs consist principally of spares, propellant, experiment fluids, and potential experiment update equipment.

4.1.4 PHASED FUNDING REQUIREMENTS. The phased funding requirements for the individual common modules are presented by fiscal year in Figure 4-2, which shows the funding requirements accumulated for the three common modules.

The modules are developed in an essentially parallel integrated program keyed to the launch schedule and in turn to the launch date of the space station. No attempt was made to phase tasks or scheduling to reduce the peak of the funding requirement.

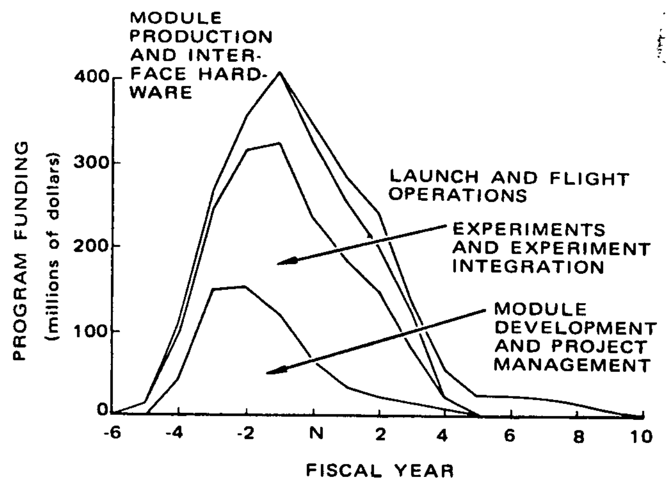


Figure 4-2. Funding Schedule

4.2 DEVELOPMENT PLAN AND SCHEDULES

The experiment module program development and manufacturing schedules summarized in Figures 4-3 through 4-5 were paced by the FPE (functional program element) launch dates specified by NASA, MSFC. All dates are relative to the space station launch date at the beginning of year "N". The launch schedule used is presented in Figure 4-6.

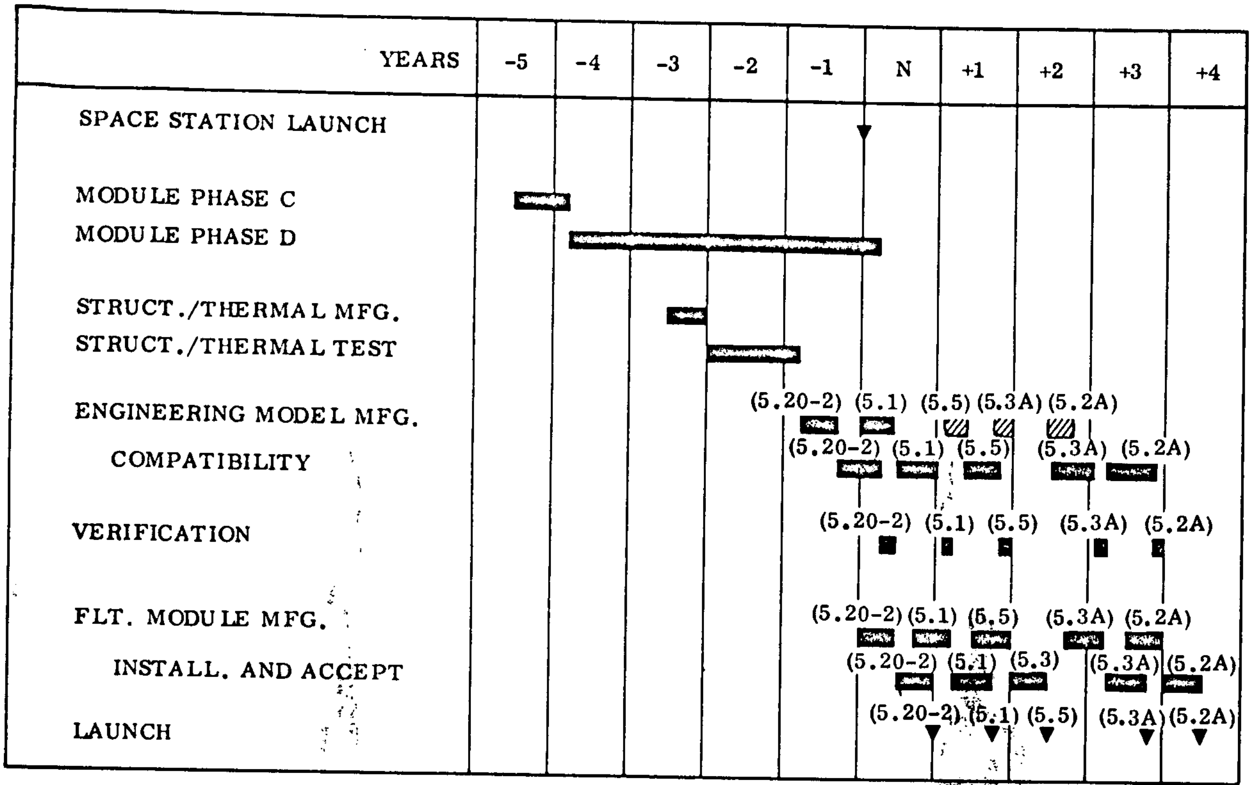


Figure 4-3. CM-1 Summary Schedule

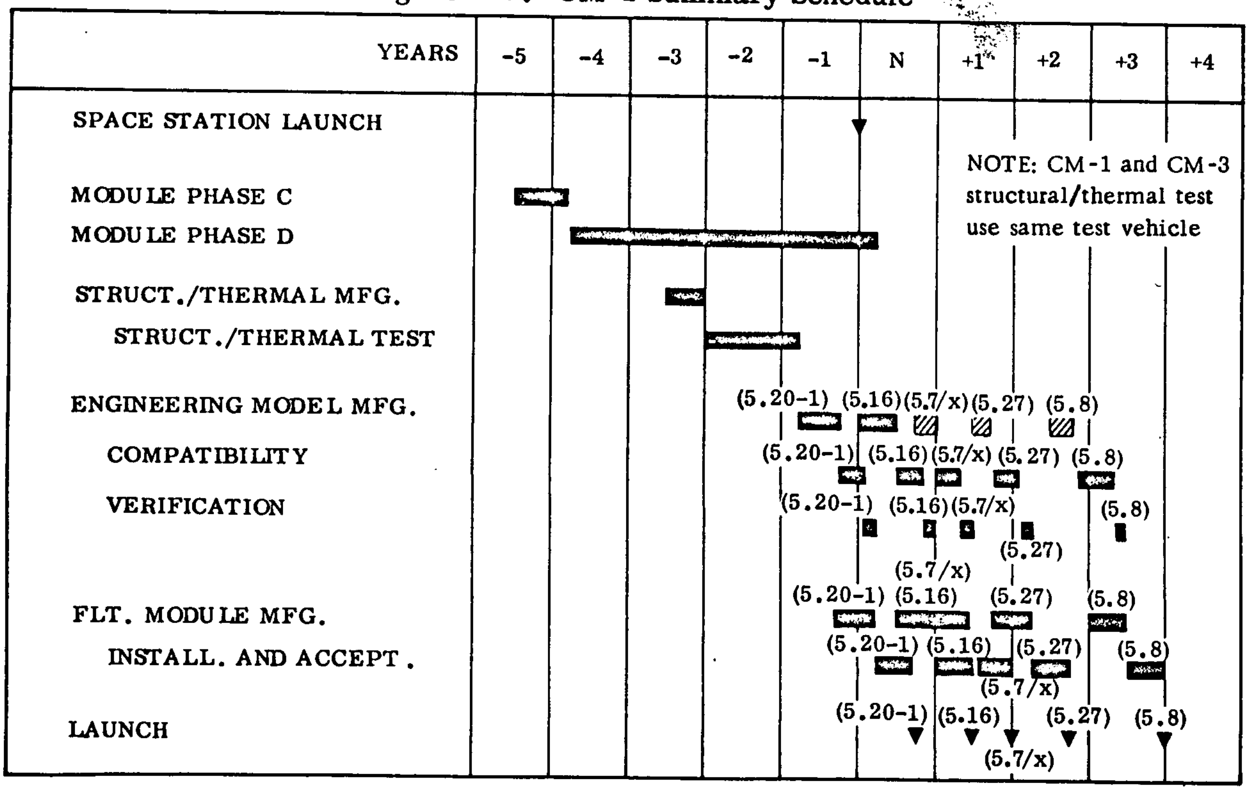


Figure 4-4. CM-3 Summary Schedule

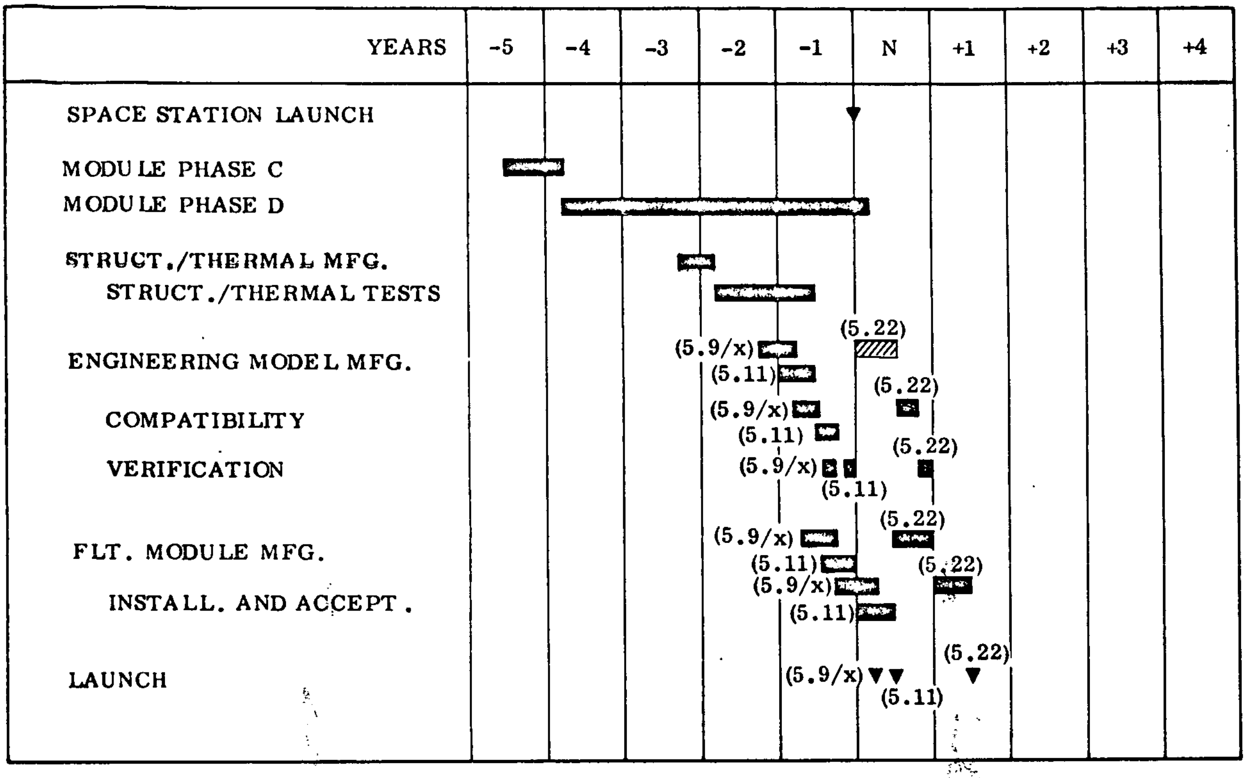


Figure 4-5. CM-4 Summary Schedule

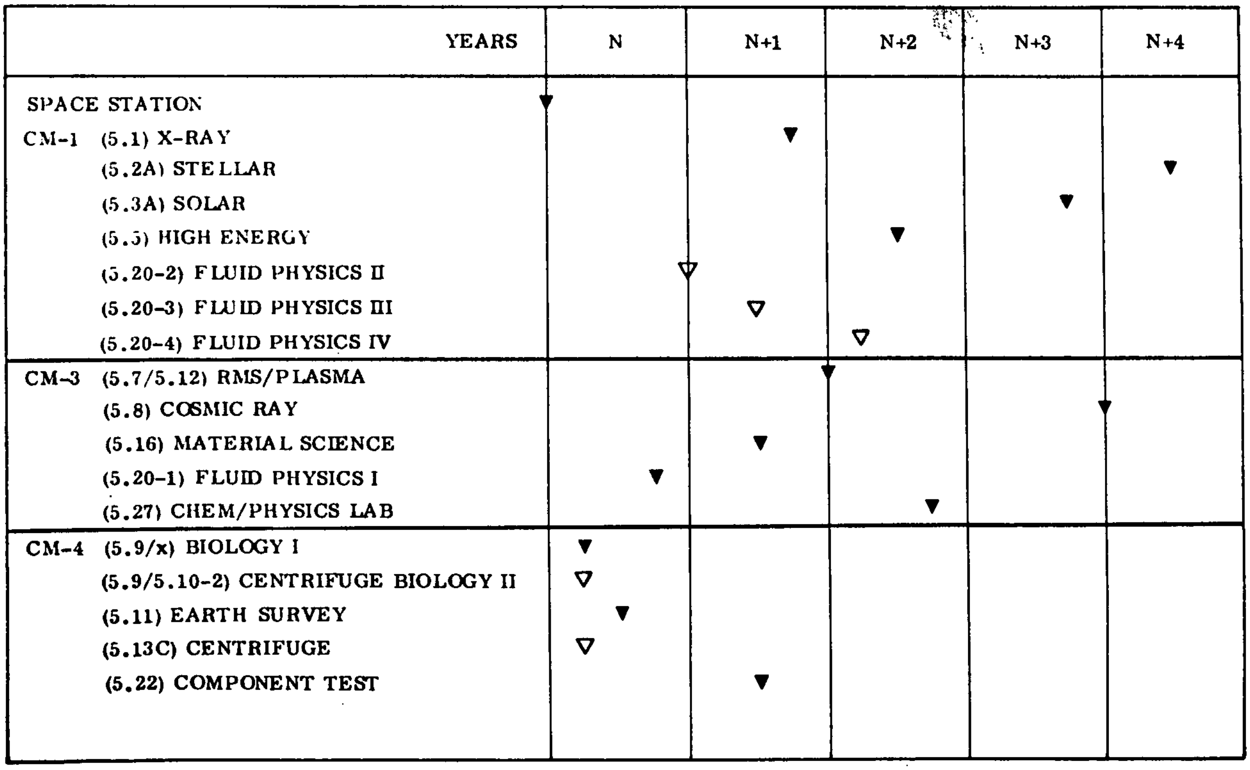


Figure 4-6. Experiment Module Launch Schedule

4.3 SRT/ART SUMMARY

Table 4-2 identifies and summarizes those major technical areas required to permit orderly and expedient development of the common module. All are needed to support phase B and C decisions regarding technical approaches to major design problems.

The criticality code I and II refers to the importance of the particular item to the common module concept. Those in I relate directly to module definition. Those in II are slightly less important because they cover interface areas rather than the common module design or deal with improvement of existing techniques.

Table 4-2. SRT/ART Requirements Summary

SUBSYSTEM	FUNCTIONAL REQUIREMENT	STATE OF THE ART	KNOWN CURRENT WORK	NEEDED SRT/ART	CRITICALITY
Reaction Control	Refueling	Conceptual Design	No Hardware Program	Hardware Demonstration	II
Stability & Control	Pointing Stability for Astronomy Experiment Concept Selection	0.1 arc-sec	No Major Program	0.005 arc-sec	I
Stability & Control	Momentum Dumping Concept Selection	Gravity (Skylab) Magnetic (OAO)	No Major Program	Torque Source Selection, Control Law Development	II
Communication/Data	High Density, Transfer Rate Data Storage	Digital - 10^8 bits/1800 ft; Tape - I/O = 1 Mb/s; Video - 10^{10} bits/2200 ft, 6 MHz bandwidth; Film - 800 bits/mm^2	Several Major Programs are Underway	10^{10} to 10^{12} bits with Selectable Output Rate of 20-40 Mb/s	II
Thermal Control	Long-life Radiator Coatings	α/ϵ = 0.4/0.85 and Degrades With Time	Several Major Programs Are Underway	α/ϵ = 0.2/0.9 Stable	II
Thermal Control	Telescope Thermal Control	± 5°F	No Major Program	± 0.1°F	II
Environmental Control/ Life Support	Contamination Control	Control of contaminants from man and spacecraft equipment for several months	None Dealing With the Experiment Contaminant Problem	Study of Experiment Contaminants & Their Control	II

SECTION 5

SHUTTLE-ONLY OPERATING MODE

The fundamental hardware elements for shuttle-only operation of the NASA candidate experiment program are:

a. Integrated common experiment modules CM-1 (free flying), CM-3, and CM-4 (attached), together with the propulsion slice.

b. Support modules capable of supplying on-orbit crew life support, power, data management, and other services normally provided by a space station — this for periods of up to five or up to 30 days.

c. Dormancy kits (power, data management, etc.) to enable normally attached experiment modules to remain in orbit while the shuttle orbiter returns to earth.

d. The shuttle orbiter itself.

The support modules are basically derivatives of the CM-3 common module.

Three fundamental operating modes were developed. They are illustrated in Figure 5-1 together with the assigned experiment groups.

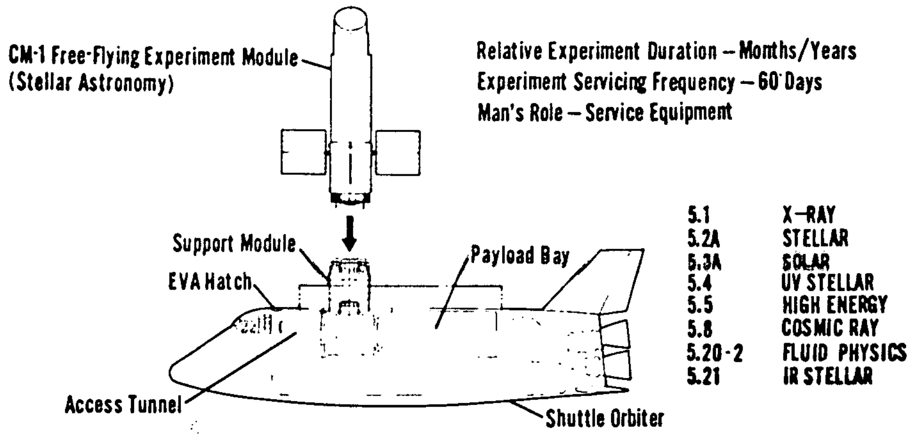
Several support/experiment module combinations exceed the shuttle payload bay length of 60 ft. All combinations exceed the 25,000 lb to 270 n.mi./55 deg orbiter payload capability and are accommodated by launch to lower altitude/inclination orbits or by launch separately with subsequent orbital redezvous. Figure 5-2 illustrates the basic shuttle payload capability and the additional capability provided by the module on-board propulsion. Figure 5-3 shows the total weights of experiment module/support module combinations.

Experiment requirements can in general be satisfactorily met. Where the orbiter stability is inadequate, experiment module subsystem capability is used. The preferred ground station system for data handling is an updated MSFN with 10 Mbps digital and 16 MHz rf video/analog capability.

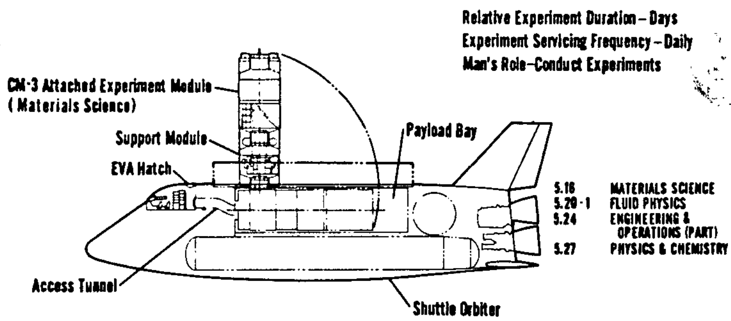
The support module itself weighs about 11,800 lb for a 2-man, 5-day stay version, 16,300 lb for a 2-man, 30-day stay version, and 20,500 lb for a 4-man, 30-day stay version. The two-man version is shown in Figure 5-4. By ground rule, the support module has to remain attached to the shuttle orbiter at all times.

Utilization of the 5-day stay version was found early to force an unreasonable number of shuttle flights in order to implement the experiment program, and to deny certain experiments altogether. The 30-day stay capability, however, increased experiment realization while reducing the number of supporting shuttle flights and hence the overall program cost.

Free-Flying Concept



Attached Concept



Attached/Free-Flying Concept

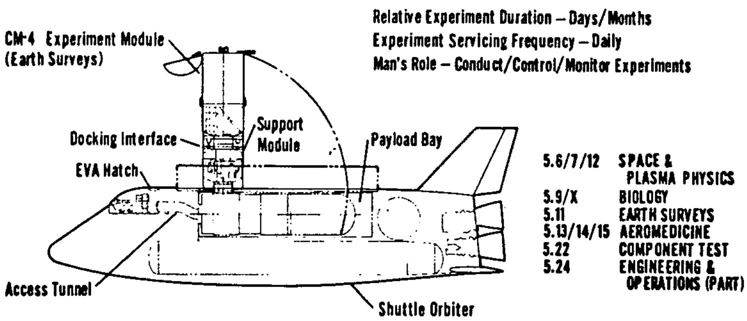


Figure 5-1. Shuttle-Only Operating Concepts

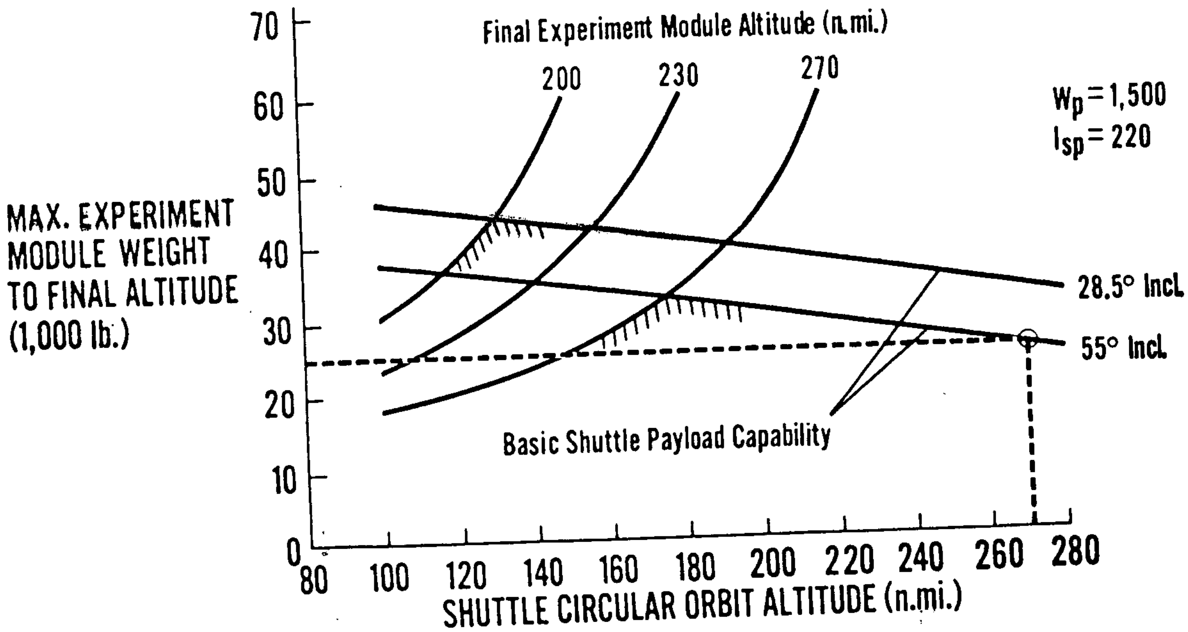


Figure 5-2. Shuttle Payload/Module Transfer Orbit Capability

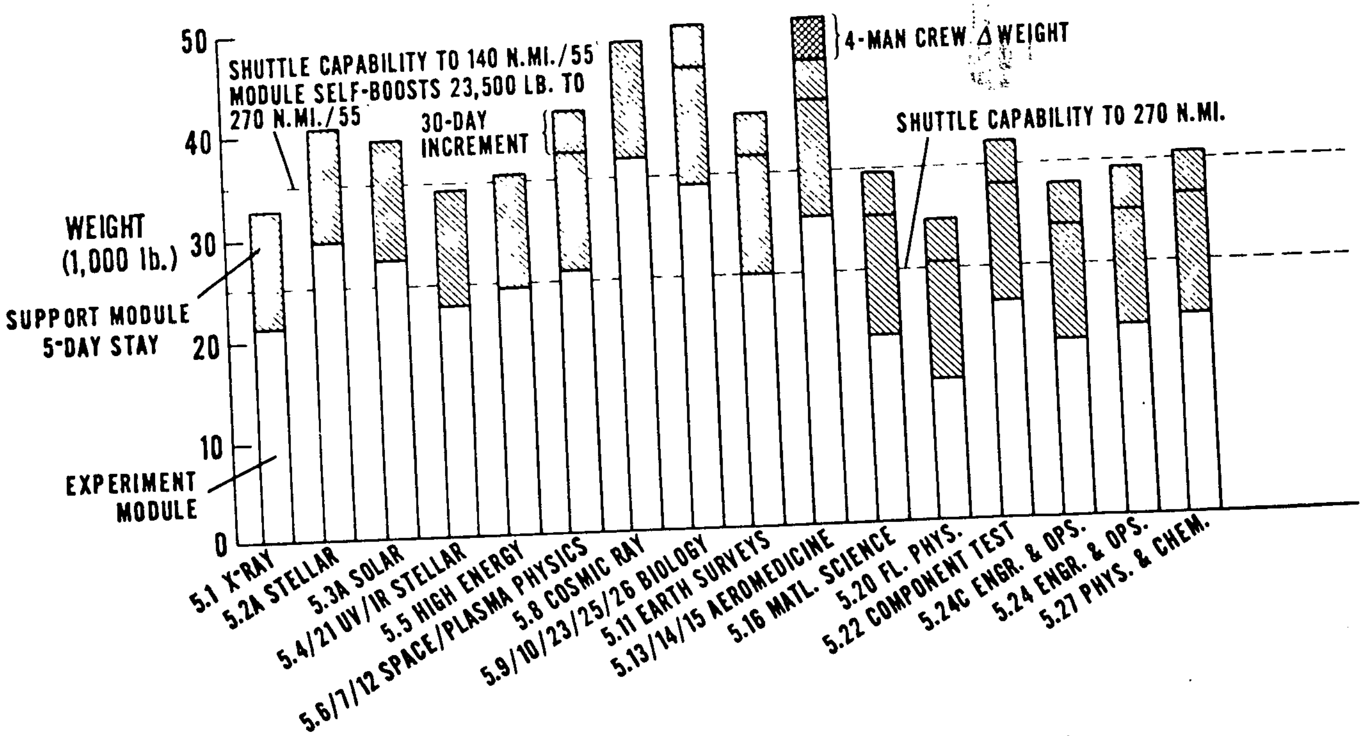


Figure 5-3. Weight Requirements of Module Combinations

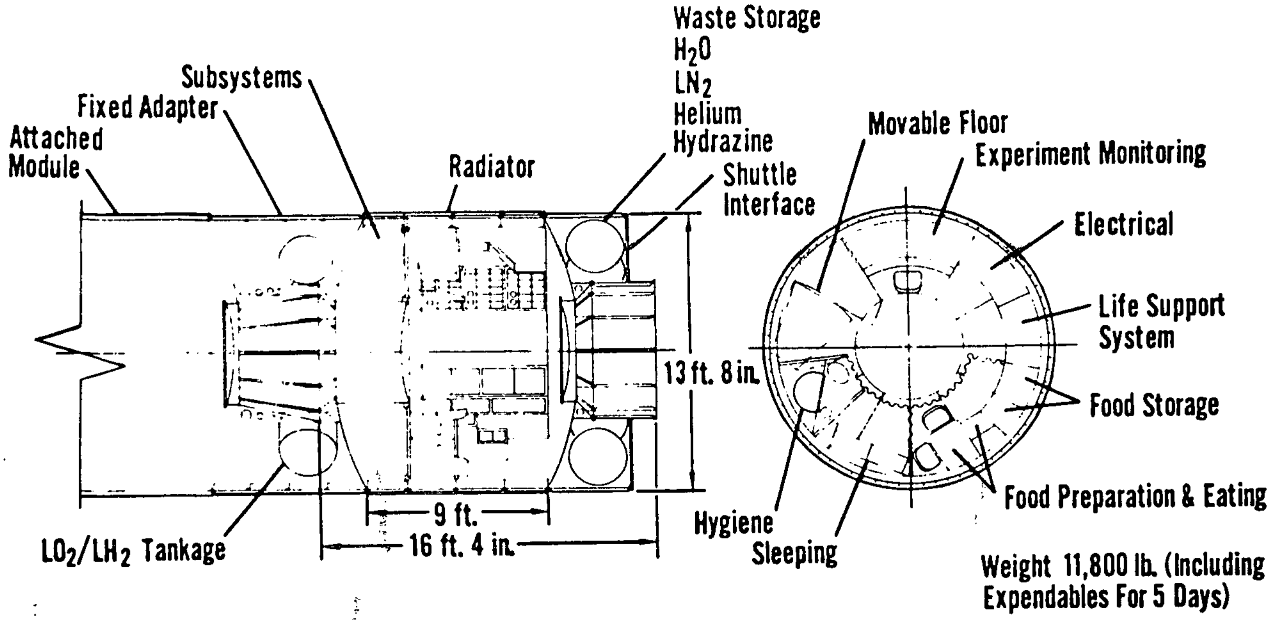


Figure 5-4. Support Module — Two Men

Preliminary program cost estimates were:

a.	Approximate full experiment program with 30-day on-orbit capability	\$4.2B
b.	Approximate full experiment program with 5-day on-orbit capability	\$6.0B
c.	Restricted experiment program with 5-day on-orbit capability	\$2.1B

These costs are for a four-year implementation period. They cannot be directly compared with the costs derived in the mainline study for a space-station-supported experiment module program since no prorating of space station costs for module support was made and the shuttle-only task embraced the entire Blue Book complement of experiments. The associated funding spread for case a above is shown in Figure 5-5.

If the shuttle orbiter is to support experiment module operations of the type discussed in this report, then the impact of these requirements should be reflected in orbiter design. Two important requirements uncovered are for a minimum 30 days on-orbit stay time, and for RCS sizing in the 150-lb thruster range to supplement the existing 1500-lb thrusters and minimize stabilization propellant requirements.

A viable experiment program can be conducted in the shuttle-only mode under the conditions quoted. The experiment module concepts already developed are compatible with this mode of operation. The support modules required exhibit considerable commonality

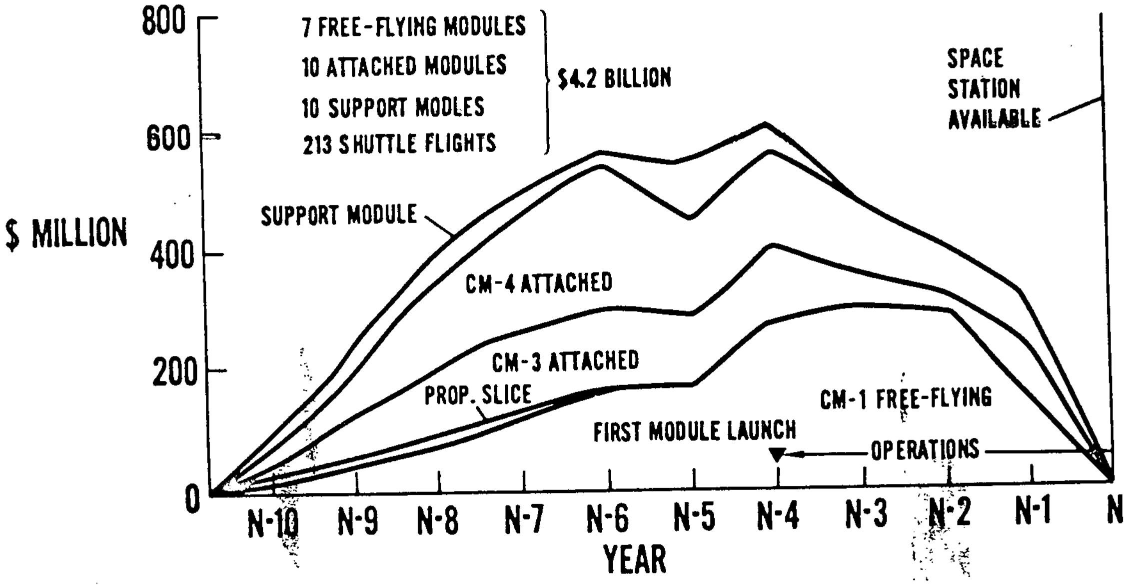


Figure 5-5. Phased Funding, 30-Day On-Orbit Case

with the experiment module concepts. Implementation in the 30-day stay mode requires 7 free-flying modules, 10 attached modules, 1 propulsion slice, 10 support modules and 213 supporting shuttle flights over a 4-year period.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

a. Substantial cost savings can be achieved by the use of common experiment modules, amounting to about 50 percent of a comparable custom module approach.

b. The concepts developed comprise one free-flying and two attached (to space station) modules, together with a propulsion "slice" and certain experiment-peculiar integration hardware. These concepts accommodate the "typical" candidate experiment program with adequate reasoned growth allowances to ensure flexibility in meeting currently unspecified experiment requirements. Man-maintainability provides an operational cost-effectiveness not otherwise achievable. The presence of man is mandatory to the execution of much of the experiment program.

c. The use of a separate transporter vehicle for on-orbit propulsive operations does not appear justifiable on cost grounds alone.

d. The level of subsystem redundancy above that demanded by safety considerations can be optimized for cost against the reduction in necessary servicing trips.

e. A viable orbital experiment program can be conducted in the shuttle-only mode of operation.

f. The common module approach to experiment implementation has the flexibility to fit any selected space program option.

6.2 RECOMMENDATIONS

a. Further development of the experiment module program should be based on the common module concept.

b. Experiment definition should be paced to match experiment module development.

c. Further study of module commonality is needed on a wider program basis.

d. The effects of assigned funding levels or selected space program options on the related experiment module program require detailed investigation.

INDEX OF FUNCTIONAL PROGRAM ELEMENTS

FPE NO.	TITLE	BASIC STUDY ASSIGNMENT
5.1	Grazing Incidence X-Ray Telescope	Module
5.2A	Stellar Astronomy Module	Module
5.3A	Solar Astronomy Module	Module
5.4	UV Stellar Survey	Space Station
5.5	High Energy Stellar Astronomy	Module
5.6	Space Physics Airlock Experiments	Space Station
5.7	Plasma Physics & Environmental Perturbations	Module
5.8	Cosmic Ray Physics Laboratory	Module
5.9	Small Vertebrates (Bio D)	Module
5.10	Plant Specimens (Bio E)	Module
5.11	Earth Surveys	Module
5.12	Remote Maneuvering Subsatellite	Module
5.13	Biomedical & Behavioral Research	Space Station
5.14	Man/System Integration	Space Station
5.15	Life Support & Protective Systems	Space Station
5.16	Materials Science & Processing	Module
5.17	Contamination Measurements	Module
5.18	Exposure Experiments	Module
5.19	Extended Space Structure Development	Space Station
5.20	Fluid Physics in Microgravity	Module
5.21	Infrared Stellar Survey	Space Station
5.22	Component Test & Sensor Calibration	Module
5.23	Primates (Bio A)	Module
5.24	MSF Engineering & Operations	Space Station
5.25	Microbiology (Bio C)	Space Station
5.26	Invertebrates (Bio F)	Space Station
5.27	Physics & Chemistry Laboratory	Module